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Volume II

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ANALYTICAL INVESTIGATION OF MEDIUM STOL TRANSPORT STRUCTURAL CONCEPTS

Volume II – Isogrid Fuselage Study

R. E. Adkisson
G. V. Deneff
Et Al

Douglas Aircraft Company
McDonnell Douglas Corporation

TECHNICAL REPORT AFFDL-TR-74-109, VOLUME II
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Air Force Flight Dynamics Laboratory
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

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FOREWORD

The analytical study described in this report was performed by Douglas Aircraft Company, McDonnell Douglas Corporation, Long Beach, California and sponsored by the Air Force Flight Dynamics Laboratory (AFFDL), Wright-Patterson Air Force Base, Ohio. The work was conducted under contract F33615-73-C-3049 Project 1368 and Task 0212. Lt. J. E. Malinak (AFFDL/FBR) was the project engineer for the work conducted.

This report covers work conducted between March 15, 1973, and June 24, 1974. This report was submitted by the authors on 26 July 1974, for AFFDL review. This report is also released as McDonnell Douglas report MDC-J6625A for internal control at the Douglas Aircraft Company.

This report is published in two volumes. Volume I, Study Results, presents the capabilities and costs of the baseline medium STOL transport wing, fuselage, and empennage structural concepts. This volume also includes the concept improvements resulting from the integration of new structural geometries, new materials, and manufacturing advances along with the resulting aircraft cost and performance payoffs. Volume II, Isogrid Fuselage Study, presents: (1) the design and analysis of a new isogrid fuselage concept, (2) the associated manufacturing methods and nondestructive inspection techniques, and (3) an aircraft cost and performance analysis for the isogrid fuselage and the new wing and empennage concepts, described in Volume I.

Mr. R. E. Adkisson was the Program Technical Director for Douglas Aircraft Company. Principle investigators in the associated disciplines include R. E. Adkisson - Structural Design, G. V. Deneff - Structural Analyses, B. J. Alperin - Material and Processes, R. L. Zwart - Manufacturing, M. L. Platte - System Analysis, and D. P. Marsh - Weight Engineering.

This technical report has been reviewed and is approved.

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ABSTRACT

Results of a study program to evaluate application of the isogrid structure concept to a medium STOL transport aircraft are presented. Isogrid is an integrally stiffened panel concept incorporating a triangular arrangement of the stiffening material which has been used successfully on space vehicle structure. The fuselage shell structure of the projected C-15 production airplane is used as the study (and baseline) component. The isogrid concept is evaluated for structural integrity, weight, manufacturing methods, applicability of NDI methods, production and life cycle costs, and aircraft performance payoffs. Structural integrity analyses of both the isogrid and the baseline concepts are based on a common set of requirements for ultimate strength, fatigue, and damage tolerance. Because of generally lower stress levels and a general absence of rivet and bolt holes in basic isogrid structure, fatigue and damage tolerance are of reduced criticality relative to baseline structure.

Aluminum materials (7475 plate selected) are the best choice for minimum production cost and weight for isogrid. The isogrid concept, as applied to the C-15 fuselage, however, is shown to be penalized in cost and weight by the following adverse configuration characteristics: (1) high wing and fuselage mounted landing gear which require heavy supporting frames; (2) significant areas of non-circular fuselage section which also require additional frames; (3) significant fuselage areas of double contour shape which result in increased forming costs; and, (4) low panel loadings which result in minimum gage machining constraints. The isogrid fuselage shell is approximately six percent heavier and 65 percent costlier to produce on a participating structure basis. Cost estimates are based on a 'bottom-up' detailed analysis approach for labor and materials. Applications of isogrid to other structural components on an engineering judgment basis are also considered.

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LIST OF ABBREVIATIONS AND SYMBOLS

SYMBOL		UNITS
AGE	Aerospace ground equipment	
A.J.	Assembly jig	
ATP	Auxiliary tool-production	
b	Rib width	inches
BM	Bending moment	
C.G.	Center of gravity	
CKF	Check fixture	
D	Bending stiffness	Pound $inches^2$
ed db	Decibels	
D_R=ni/Ni	in Miner's fatigue equation	
E	Modulus of elasticity	PSI
f	Frequency of occurrences	
fc	Coincidence frequency	
FRP	Fuselage reference plane	
F/S	Full size	
G&A	General and administrative	
G.A.G.	Ground-air-ground	
H	Rib spacing	inches
H.F.	Hoist fixture	
HFLD	Handling fixture - line dolly	
HFPR	Handling fixture - production	
HL'S	Holes	
Hz	Hertz	CPS
K	Extensional stiffness	PPI
L	Length	
L.F.	Load factor	
LH	Left hand	
M	Moment	
MC	Mill cutter	
MCM	Machine central medium	
MF	Mill fixture	
n	Actual member of cycles	
N	Allowable number of cycles or applied load	
NC	Numerically controlled	
NT	No tool	
O.C.	On centers	
P	Cabin pressure or load	
PACE	Planning aircraft cost estimating	
PME	Prime mission equipment	
POL	Petroleum, oil, and lubricant	
QR&A or QRA	Quality, reliability, and assurance	
R	Radius, stress ratio, or coordinate	inches
RH	Right hand	
RDT&E	Research, development, test, and engineering	
S	Plate depth	inches
t	Skin thickness	inches
$\bar{t}$	Weight thickness	inches
T	Torque	
TL	Transmission loss	db

LIST OF ABBREVIATIONS AND SYMBOLS (Continued)

SYMBOL		UNITS
u_a	Speed of sound in air	
V	Shear	
w	Radial deflection	inches
$\alpha = bd/th$	Isogrid geometry constant	
$\beta = f(\alpha, \delta)$	Isogrid geometry constant	
γ	Knockdown factor in isogrid compression instability equation	
$\delta = d/t$	Isogrid geometry constant	
θ	Coordinate	
λ	Wavelength	
ρ	Density	pounds per cu. in.
σ	Stress	PSI
ν	Poisson's ratio	
b, B	Bending	
cr	Critical	
EFF	Effective	
i	Element number	
NOM	Nominal	
S	Shear	
T	Torque	
X,Y,Z	Axes of aircraft or loads	

SECTION I

INTRODUCTION AND SUMMARY

1.1 INTRODUCTION

The establishment of lightweight and economical structural concepts for aerospace structures is a continuing objective of the Air Force and the industry. Stability-critical structures form a major portion of all aircraft, booster, and space vehicle structures. Aircraft such as the DC-8, -9 and -10 use a mechanically attached stringer, frame and skin construction which is a 0-90 degree stiffened structure. Boosters, as exemplified by the S-II second stage, duplicate aircraft 0-90 degree patterns with a constant height, integral machined pattern. The S-IVB stage, as well as the Thor, employ square patterns rotated through 45 degrees. All of these patterns are efficient in certain load regimes. However, they are basically four-bar links which are in-plane rotationally restrained by the skin and exhibit little out-of-plane torsional resistance capability.

In 1964, Dr. Robert R. Meyer of McDonnell Douglas Astronautics Company (MDAC) set out to find a structural arrangement that negated the shortcomings of the 0-90 degree and 45 degree patterns without introducing other penalties such as increased weight. The concept found to be the most promising was isogrid, a triangulation of the stiffening (hereinafter referred to as rib) members. This stiffening concept is now in use as structure for Delta vehicle tanks, interstages and shrouds, and Orbital Workshop interiors.

The name isogrid is coined from the word isotropic. This is because isogrid acts like a monocoque (isotropic) plate, in that both the skin and ribs resist loads irrespective of the load direction. The rib grid provides relatively high out-of-plane torsional rigidity as well as good resistance to general instability failure. Isogrid structure can be designed to withstand compression and shear without internal support. Out-of-plane loads can be resisted by the isogrid ribs and skin and the nodes at rib intersections provide natural points for attachment of required installations.

Limited full scale and model testing has been conducted by McDonnell Douglas which have served to verify the structural concept. The basic efficiency of isogrid is indicated in Figure 1, where compression optimized aluminum cylinders are shown to be lighter than typical aircraft fuselage and booster structure. A final comparison, including the effects of shear and manufacturing limitations, however, will modify the data shown on that figure.

Isogrid is, by its nature, an integral structure, being machined from plate stock. Current concepts are to make elements of isogrid structure out of the largest possible pieces of plate stock. The resulting reduction in parts suggests economies in construction. The data in Table I compares manufacturing costs of a stringer stiffened skin shroud and an isogrid shroud, both of which are currently being built by McDonnell Douglas. The isogrid cost (hours/lb) is less than 40 percent of the stiffened skin cost. This trend resulted from the drastic reduction in parts and use of node holes for attachment of subsystem equipment.

Douglas Aircraft Company has an on-going IRAD program to evaluate metal isogrid for an Advanced Short Range Aircraft (ASRA). This study to date has

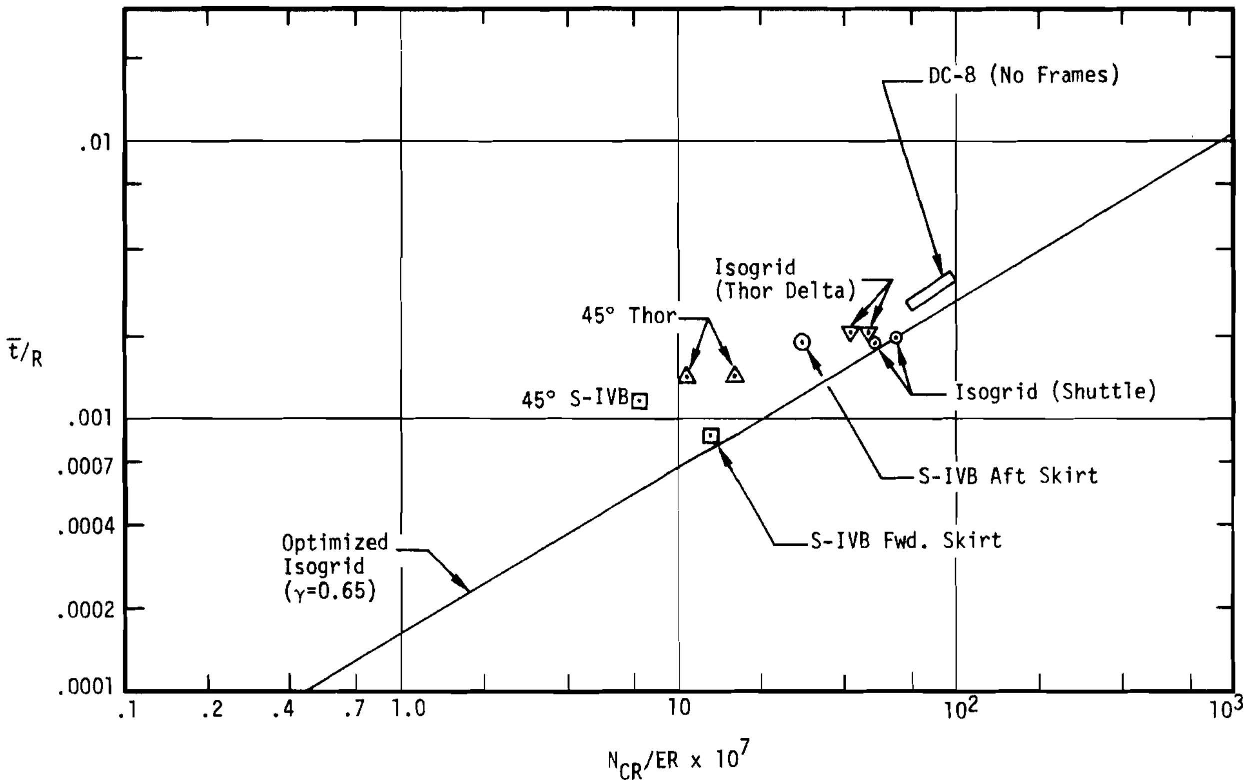


Figure 1 COMPARISON OF STRUCTURAL EFFICIENCIES

TABLE 1 MISSILE PAYLOAD SHROUD COST COMPARISON		
COST ITEM	DELTA (8 FOOT DIAMETER -ISOGRID)	TITAN (10 FOOT DIAMETER -OUTSIDE STRINGERS INSIDE RINGS)
NUMBER OF DRAWINGS	85	150
ENGINEERING HOURS	26,000	60,000
TOOLING HOURS	30,000	60,000
MANUFACTURING COST (HRS/LB)	3.1	8.0

shown that an isogrid fuselage is feasible and is weight competitive with a stringer skin fuselage. The isogrid structure is frameless except for door jambs and window pane support forgings. Wing to fuselage loads are reacted by integral reinforced isogrid sections in the wing area.

The hardware applications previously noted clearly establish isogrid as a potential candidate structure for aircraft. Development of its full potential and establishment of its best usage remains the subject of specific design studies. This study is primarily directed to the application of isogrid to the C-15 AMST fuselage.

1.2 SUMMARY

Areas of potential application of isogrid to the AMST are identified and the advantages and disadvantages of these applications are discussed qualitatively in Section II. Areas of potential cost and weight efficient application are indicated generally to be flat or of single contour surface shapes. These include pressure (and other) bulkheads, spar webs, doors, leading edges, wide frames and torque boxes. A preliminary isogrid design was prepared for the fuselage barrel section extending from Station 366 to 982. Isogrid requirements were further extended to Station 1437 by simplified analyses. Results of the study indicate that the C-15 fuselage incorporates characteristics (such as out-of-round sections, double curvature surfaces, high wing, low loadings, etc.) which are detrimental to the efficient weight and cost application of isogrid. The fuselage isogrid design strengths and weaknesses are further discussed in Section II. The design and analysis of the basic isogrid panels, joints, component interface, and reinforcement patterns are presented in Sections III and IV. The structural analyses show adequate margins for ultimate strength, fatigue, and damage tolerance, with general instability being the critical mode. The isogrid fuselage thus defined is six percent heavier than the baseline C-15 vehicle fuselage.

Manufacturing methods are discussed in Section V. Techniques for milling isogrid patterns in flat plates are outlined. Methods of forming the panels into "barrel staves" of either singular or compound curvature are presented. Shot peen forming is identified as promising for compound curvature. Further developments required to improve cost effectiveness are discussed.

Section VI identifies ultrasonic and penetrant non-destructive techniques respectively for material and fabrication inspection.

Section VII is an extensive bottoms-up cost analysis comparison of the baseline and advanced concept aircraft. Isogrid fuselage shell structure for the C-15 AMST is identified as significantly more costly than the baseline structure. The cost problem areas identified include high costs for capped isogrid machining and compound curvature forming. Their effect on costs are included.

Product cost and airplane performance potentials attendant to the use of isogrid are evaluated in Section VIII, these data being compared to the baseline airplane. Performance payoffs are determined for both resized and unresized aircraft.

A final section, IX, presents conclusions and recommendations. The strong points and limitations of isogrid are discussed and recommendations for further work are presented.

SECTION II

ISOGRID STRUCTURAL APPLICATION

This section discusses potential applications of the isogrid structural concepts for the AMST aircraft. These comments are qualitative, and are based on engineering judgement except that the fuselage comments are based on the results of the design and analysis study reported in the subsequent sections. The application areas, other than the fuselage shell, are highlighted in Figures 2 and 3, and summarized on Table II. The pay-off of an isogrid structure application to a particular airplane can, of course, only be determined by unique indepth studies.

2.1 ISOGRID APPLICATIONS TO FUSELAGES

2.1.1 Fuselage Shell

Isogrid frameless shells are feasible for booster shell structures such as MDAC's current Delta vehicle. However, aircraft loadings are more complicated and consideration must be given to wing-to-fuselage loads, gear-to-fuselage loads, floor loads, cutouts, non-circular fuselage sections, and double curvature. The AMST is a high wing aircraft and the wing/gear loads are best resisted by conventional frames. Floor loads can be resisted by local reinforcing of the shell wall above and below the floor. Cutouts in a fuselage shell are handled by leaving reinforcements in the isogrid pattern around the opening and providing framing for openings larger than a conventional window. For non-circular fuselage sections subjected to internal pressure, frames are necessary with isogrid to maintain fuselage section shape. The minimum weight of the isogrid structure is established by machining capability and tolerances. The resulting minimum section is overstrength in low load areas (e.g., in the fuselage forward of the wing), such that some sections are twice as heavy as required by loading requirements only. Isogrid in double-curved sections has not been made. A large percentage of the surface area of the AMST fuselage is double curved. This is a problem since double-curvature forming is a major cost element.

In summation, the baseline aircraft has many features that are unfavorable to the use of an isogrid fuselage structure. The high wing configuration, non-circular section, and low loading levels penalize the isogrid weight. Subsequent unpublished IRAD work show that isogrid patterns with two rib depths (low ribs inside of high ribs) reduce the weight penalty in low loaded areas. The double curvature penalizes the isogrid cost. Application to other aircraft must consider these factors to determine the final applicability.

2.1.2 Wide-Frame Applications

Wide frame applications involve a sandwich arrangement of two isogrid panels tied together by webs or trusses. An example of this is shown in Figure 2. In this application, one panel is the isogrid outer shell and the inner panel is an open isogrid wall. The design replaces all frames including the tail support frames. The arrangement has great torsional stiffness (a requirement in this area), and will possess the inherent light weight of trusses. The open inner wall provides access to lines or cables located between the walls and attached to the node points.

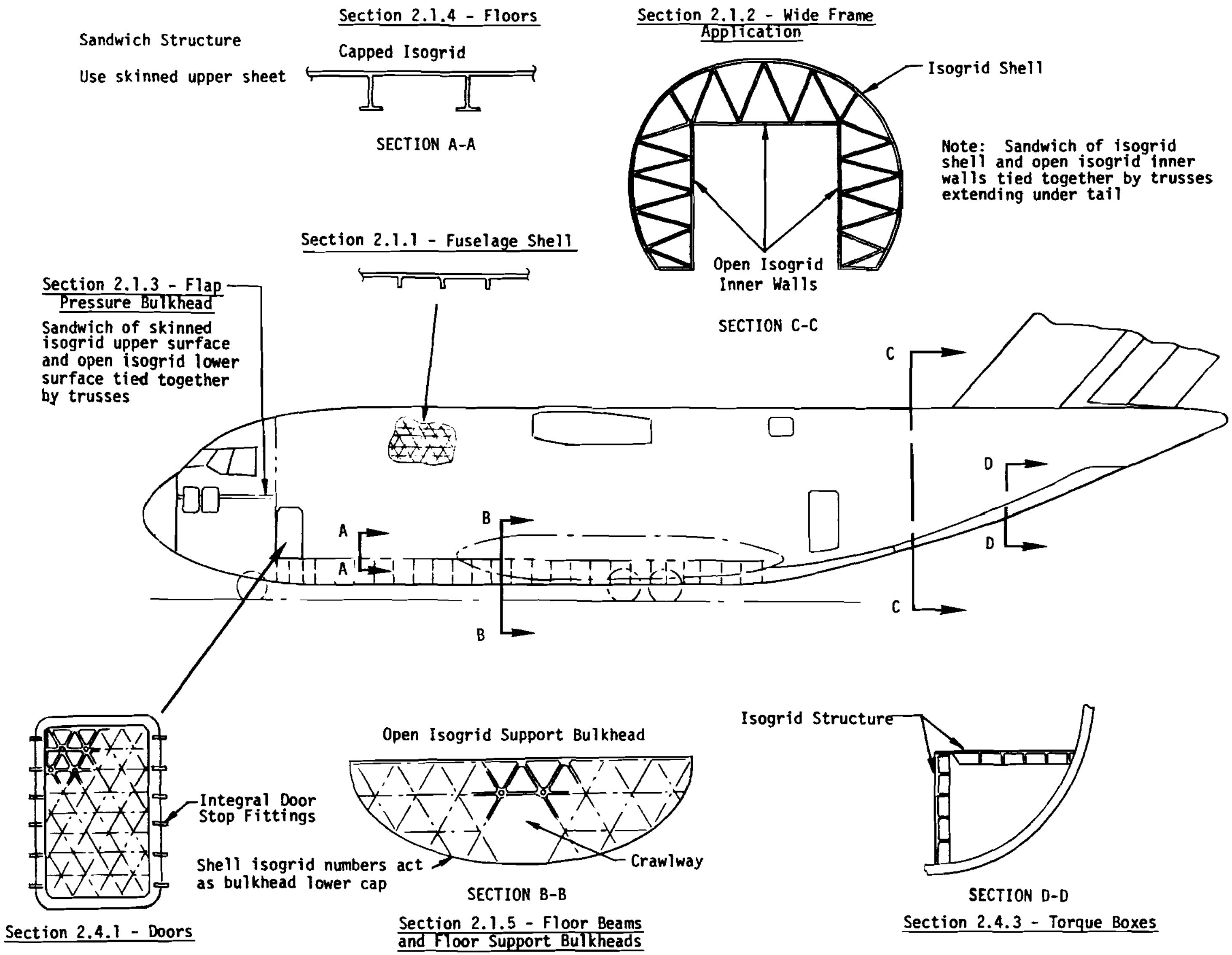


Figure 2 FUSELAGE ISOGRID STRUCTURAL APPLICATIONS

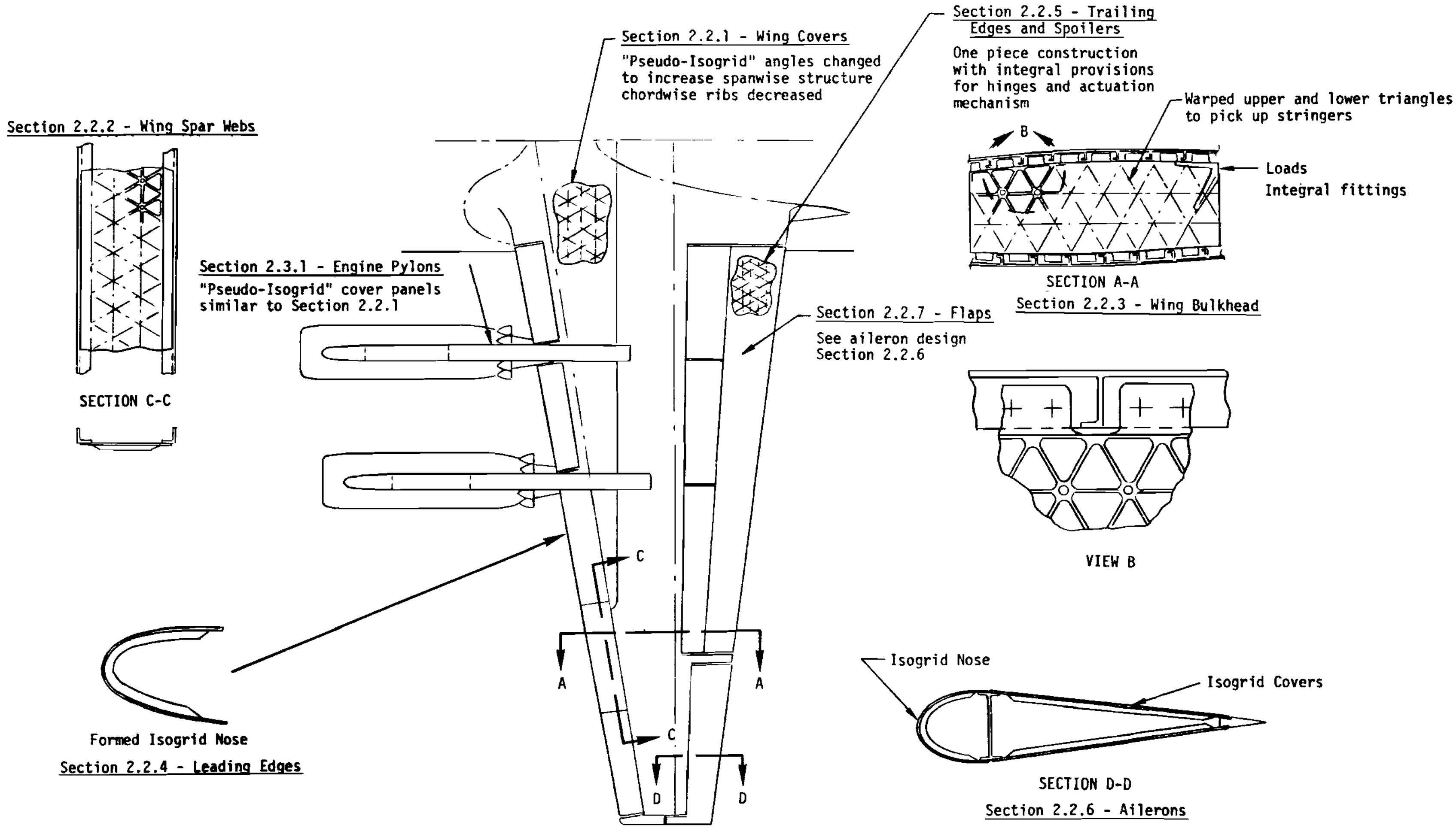


FIGURE 3 WING ISOGRID STRUCTURAL APPLICATIONS

TABLE II ENGINEERING JUDGEMENT EVALUATIONS OF ISOGRID APPLICATIONS

APPLICATION	AMST AIRCRAFT		
	COMMENTS	ISOGRID RELATIVE WT RE CONVENTIONAL STRUCTURE	ISOGRID RELATIVE COST RE CONVENTIONAL STRUCTURE
2.1.2 Wide Frame Application	Wide frame is a sandwich of two isogrid structures tied together by webs or trusses. (See Figure 2)	Weight effect not evident. Concept potentially lighter.	Comparable
2.1.3 Flat Pressure Bulkheads	Feasible when designed as sandwich (See 2.1.2)	Comparable or lighter	Comparable or lower
2.1.4 Floors	Existing extruded plank design very efficient for AMST floor loadings	Comparable or lighter	Higher
2.1.5 Floor Beams and Floor Support Bulkheads	Flat isogrid not efficient in compression	-	-
2.2.1 Wing Covers	Standard isogrid not competitive	Standard isogrid heavier. Pseudo isogrid may be comparable.	Costs of pseudo isogrid comparable.
2.2.2 Wing Spar Webs	Isogrid can efficiently resist in-plane shears and normal loadings	Lighter in higher loaded regions	Comparable
2.2.3 Wing Bulkheads	Isogrid feasible. Ribs and skins can efficiently resist flap/aileron/gear/pressure loads.	One integral part lighter than multiple machined parts. Lighter	Trade off machining one big part for many small. Comparable
2.2.4 Wing Leading Edges	Feasible as long as single curvature and nose radius not less than allowable forming radius. Few support ribs required. Efficient.	Lighter	Number of parts reduced (ribs). Lower
2.2.5 Wing Trailing Edges & Spoilers	Current design honeycomb.	Comparable if chemically milled	Comparable or lower
2.2.6 Ailerons	Current ailerons very light weight. A minimum gage isogrid structure is heavier.	Isogrid must be chemically milled	Higher
2.2.7 Flaps	Current blown flaps in engine exhaust of titanium. Titanium unproved/unused as isogrid. Aluminum flaps light weight. Minimum gage isogrid heavier.	Isogrid must be chemically milled	Higher
2.3.1 Engine Pylons	Pylon cover panels have high shears and must be stiff.	Standard isogrid heavier. "Pseudo isogrid" may be comparable	Comparable
2.4.1 Doors	Feasible - provided contours not a problem. Efficient application.	Lighter	Comparable or lower
2.4.2 Fairings	Few fairings on AMST and these highly contoured. Isogrid not applicable.	-	-
2.4.3 Fuselage Torque Boxes	Feasible for torque boxes. Efficient application.	Comparable or lighter	Comparable or lower

2.1.3 Flat-Pressure Bulkheads

Flat pressure bulkheads can be designed using a sandwich of two isogrid panels tied together by webs or trusses. In practice one isogrid panel would be skinned and the other open. Such an application is shown in Figure 2, for the panel over the nose wheel well.

2.1.4 Floors

Floors can be made of single isogrid panels or of a sandwich concept similar to the pressure bulkhead. This application will be most weight effective when there are high in-plane shear loads in the floor, which isogrid inherently resists well. The usual critical floor load conditions involve loads normal to the floor. These loads are best resisted by members running between support structures. The existing baseline floor has extruded planks running between bulkheads. The faces of the planks between the longerons are sufficiently thick to resist local loads. This design is of reasonable weight and of very low cost. It is the proper choice for this application. Isogrid could be made as light, but would be much more expensive.

2.1.5 Floor Support Bulkheads

The baseline design involves webbed bulkheads between the floor and the bottom of the fuselage. It is warranted to replace the webs by isogrid when load conditions (such as high shear loads) require use of all isogrid members. In this situation, if the fuselage shell was also isogrid, the fuselage wall could serve double duty and act as the lower cap of the floor support bulkhead. This was analyzed and found feasible, reference Section IV. For the baseline, however, the critical loads are primarily compression, thereby making the application of flat isogrid less desirable.

2.2 ISOGRID APPLICATIONS TO WINGS

2.2.1 Wing Covers

The loads in wing covers are predominately in the direction of the span. This type of load is most efficiently resisted by stringers in the direction of the load. An isogrid cover would be less efficient than the traditional approach because the members not aligned in the load direction would be inactive. Isogrid may be effective if the cover is also loaded by very high shears. In this instance, isogrid's inherent capability to resist shear load would be of value. A further possibility exists, involving a "pseudo-isogrid" pattern with variable rib widths and triangles other than equilateral. Efficient candidate patterns should exist which provide axial and shear load capability matching the requirements.

2.2.2 Wing Spar Webs

Wing spar webs are subjected to high in-plane shears from flight loads and high normal loads from fuel tank over-pressurization. Isogrid has special capability to resist shear and to act like a beam to resist the normal pressure loading. In general, isogrid is more efficient than conventional construction when the shear or normal pressure loads are large. However, isogrid will not be as efficient as a tension field web when shear loads are low.

2.2.3 Wing Bulkheads

Wing bulkheads are used to close off the end of fuel tanks and to resist shear loads from flaps, ailerons, or gears. Isogrid is a viable concept for such conditions. Fittings can be machined integrally into the isogrid and the skin and rib gages tailored to distribute the loads to the reacting wing skin. Again, normal pressure stresses are resisted by beam action in the isogrid skin and ribs. The conventional designs have many fittings bolted together. The isogrid design is one large integrally machined structure without the (fitting) joint penalties. Hence the integral bulkhead would be more efficient.

2.2.4 Wing Leading Edges

The AMST leading edges use close spaced ribs covered by skins, and have many access doors to accommodate the slats. The ribs and skin could be replaced by an isogrid sheet formed to the contour of the leading edge and attached to the front spar at integral lands. Access doors would be unchanged. The ribs in the conventional construction provide stiffness, shear and shaping capabilities. These functions are inherent in isogrid. This is a simple direct application provided the leading edge is a single contour curve and provided the radius of the tip of the leading edge is greater than the allowable forming radius of the isogrid sheet.

2.2.5 Wing Trailing Edges and Spoilers

Both trailing edges and spoilers are designed as honeycomb panels with 0.016 inch face sheets and 3.1 lb/cu. ft. core, with the weight thickness varying from about 0.05 inches to 0.1 inches for two faces. Isogrid can be used in both applications. Typically, an isogrid spoiler can be designed as one part, where the basic machining includes the hinges and provisions for the actuation linkage. The weight thickness of a minimum gage machined isogrid design is approximately 0.07 inches and could be reduced by chemical milling. This weight thickness would go up somewhat to handle stiffening along the hinge line etc., so that the final weight will be comparable to the baseline structure.

2.2.6 Ailerons

It is possible to make the aileron structure out of isogrid with only five basic parts. These would be an isogrid leading edge, an isogrid spar, two isogrid cover panels, and a trailing edge member (not including hinging and actuation needs). The current minimum machining gage for isogrid skins is 0.045 inch including maximum tolerance. The weight thickness ($\bar{t}$) of this isogrid structure, including ribs and node penalties, would be approximately 0.07 inches per cover. This $\bar{t}$ can be reduced by subsequent chemical milling.

The current ailerons on the baseline aircraft are 0.03 inch monocoque skins on ribs approximately five inches on center. The equivalent $\bar{t}$ of this combination is less than 0.07, so isogrid would have to be chemically milled to be competitive for this application on this aircraft. It will be an acceptable application also whenever loads are sufficiently high so that heavier gages are necessary.

2.2.7 Flaps

The flaps are similar to the ailerons, hence flaps potentially can also be made out of five basic isogrid parts. The flaps on the baseline are externally blown. The flap portions behind the engines are subjected to engine exhaust flow and noise, reaching temperatures of 600°F at 135 db and are made of titanium. Flaps away from the engine exhaust are of aluminum. Both titanium and aluminum cover panels are made of 0.05 inch sheets chem-milled to 0.03 inch. The 0.05 inch dimension is associated with the pads in attach areas. Closely spaced hats are attached to these sheets for stiffening and support ribs are provided at 10 to 20 inches on center. Aluminum isogrid flaps are feasible but will have to be chemically milled to be weight competitive. No titanium isogrid structure has been made to date, although there is no reason to rule out such a concept. However, the complete lack of background makes a judgment difficult at this time. Costs should be a primary consideration.

2.3 ENGINE

2.3.1 Engine Pylons

Engine pylons require high shear load capability and should be stiff to improve flutter characteristics. Isogrid cover panels are excellent on both counts. The design in this area should also consider the "pseudo-isogrid" discussed in Section 2.2.1. The optimum pattern for this application will be something other than standard isogrid in order to be weight competitive with a conventional structure.

2.4 MISCELLANEOUS ISOGRID APPLICATIONS

2.4.1 Doors

Doors in aircraft can be grouped as either those which resist airloads and door-open loads only, or doors which carry air loads and door-closed loads. The first type of door is typically made of an outer skin stiffened with a beaded inner skin and provided with hinges and latches. Isogrid is particularly suitable for this type of door. A typical isogrid access door is shown in Figure 4. This door integrates all functions into one simple machined component. This design can be extended to applications such as gear or nacelle doors.

The second group is exemplified by a cabin door. Again, the door can be made of a fairly deep isogrid section (1 to 2 inches) designed to beam the cabin pressure loads across the door opening. The stop fittings would be integral with the door. Such doors are feasible, especially in single curvature areas.

2.4.2 Fairings

Isogrid is suitable for fairings provided the forming requirements are not too severe. Fairings are minimized on the baseline aircraft and are highly formed sections where used. Hence, this application is not of value to this aircraft.

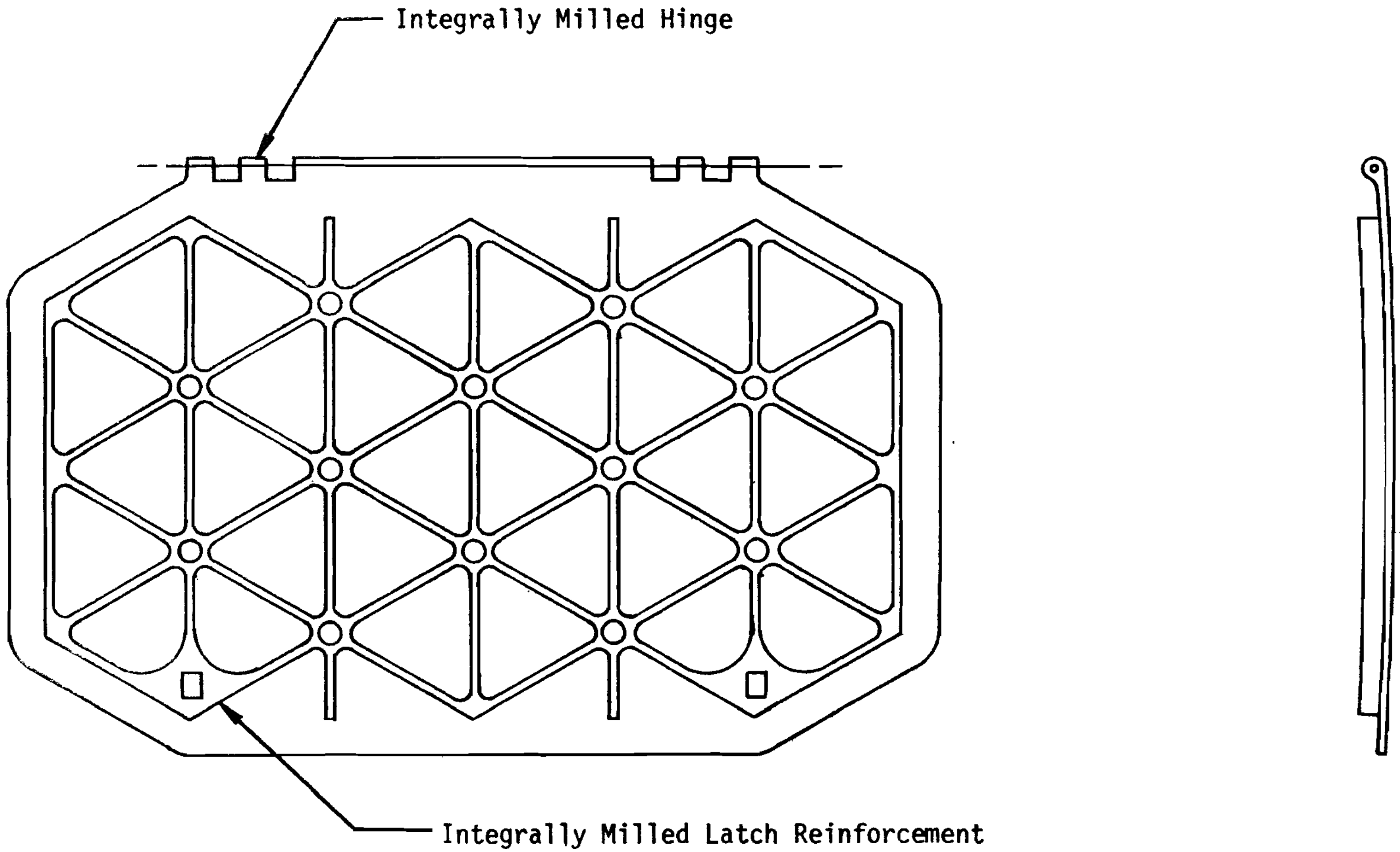


Figure 4 ACCESS DOOR APPLICATION

2.4.3 Torque Boxes

Torque boxes could be made of isogrid sections to take advantage of the shear carrying capability of this structure. The sections should be open isogrid. Skinned isogrid is needed only if a fairing provision is required. The torque boxes around the aft door of the baseline aircraft may be able to take advantage of this feature.

2.5 TAIL SECTIONS

Comments presented in Section 2.2 on the wings pertain to tail structures.

SECTION III

ISOGRID FUSELAGE SHELL DEVELOPMENT

The AMST fuselage was chosen to evaluate the feasibility of using isogrid structure. The inherent stability of isogrid shells points to the fuselage as a prime candidate for potential application. A preliminary design study was conducted. The basic isogrid sizes were defined and local reinforcement requirements determined. Major joints were designed and a means of attachment devised. Areas are identified where internal frames are needed. This design is the basis of the cost and weight analysis included in this study.

3.1 BASELINE DESIGN CONCEPT

The baseline airplane used for the isogrid study is the same AMST transport used for comparison with other structural concepts presented in Volume I. It is described in Section I of Volume I, and the structural arrangement is shown there in Figure 2. The fuselage is a conventional aluminum alloy skin, stringer, frame design based on the preliminary criteria and loads generated in the YC-15 prototype effort.

3.2 ISOGRID DESIGN CONCEPT

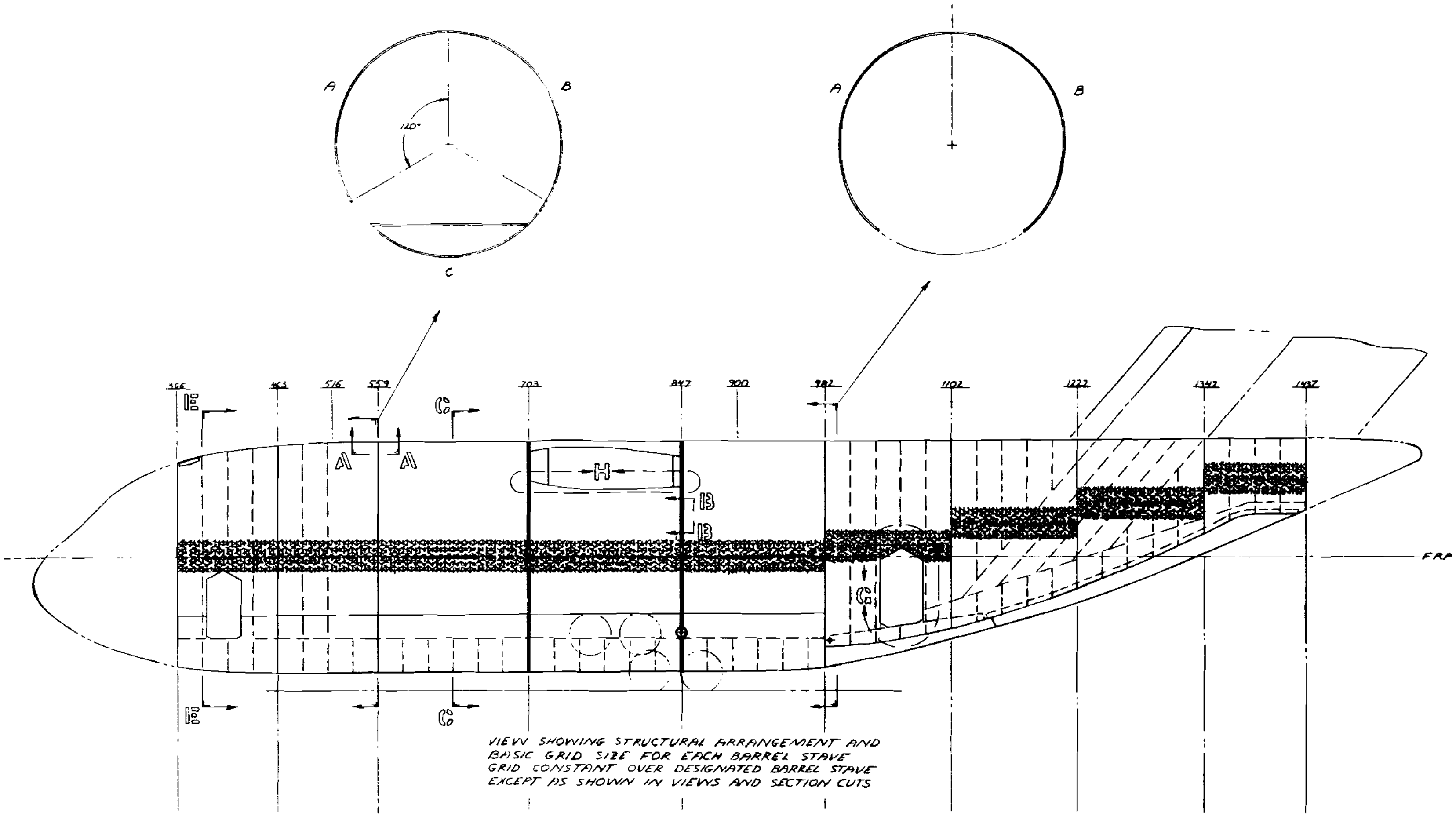
The basic fuselage shell structure is presented in Figure 5 as isogrid integrally machined from aluminum plate. The machining is performed on flat plates which are then formed into cylindrical segments. These segments are bolted together along longitudinal bolt patterns into barrels which are connected end to end to form the fuselage. The basic isogrid geometry along with longitudinal and circumferential butt joints are shown in Section A-A of the Figure.

Each barrel segment has a basic grid, i.e., basic rib spacing, plate thickness, skin gage, and rib width as shown in the main view of Figure 5. These elements were sized to resist the internal pressure and flight loads generated for the baseline airplane. The basic grid applies everywhere on the designated segment except where integral reinforcement is required around cut-outs, discontinuities, and areas of point load application as shown in pertinent section cuts and views of Figure 5. Only unflanged construction was considered for basic grid. However, flanged isogrid is also used in local, highly loaded, areas.

The material selected is 7475-T7351 aluminum plate, Figure 6. It is representative of high performance aluminum alloys and can be machined and formed. The isogrid concept is applied only to the basic fuselage shell. The doors, windows, floor, landing gear, wing, empennage, attach structure, etc. were studied only to the extent that they affected the shell. The fuselage is considered in two sections -- center and aft.

3.2.1 Center Section

The center fuselage extends from stations 366 to 982. It consists of five barrels with three segments each. Frames are located at stations 703 and 847 and spaced 24 inches O.C. in the forward two barrels as shown in Figure 5. Bulkheads are located at 24 inch intervals under the floor over the remainder of the section.



BARREL	1	2		3		4		5		6	7	8	9
STAVE	A, B, & C	A & B	C	A & B	C	A & B	C	A & B	C	A & B	A & B	A & B	A & B
S_{nom}	1.000	1.000	1.000	1.000	1.000	1.250	1.250	1.000	1.000	.900	.900	.900	.600
t_{nom}	.045	.049	.045	.055	.059	.055	.065	.045	.065	.059	.061	.057	.045
b_{nom}	.065	.065	.065	.065	.065	.100	.073	.065	.065	.065	.067	.083	.065
$\bar{t}_{theoretical}$	.0916	.0954	.0916	.1011	.1049	.1446	.1299	.0916	.1106	.1000	.1032	.1095	.0721
$\bar{t}_{made}$	.0026	.0025	.0026	.0025	.0025	.0022	.0030	.0026	.0025	.0023	.0022	.0019	.0015
$\bar{t}_{nom}$	.0941	.0979	.0941	.1036	.1074	.1469	.1329	.0941	.1131	.1023	.1054	.1114	.0735

Figure 5 ISOGRID FUSELAGE SHELL STRUCTURE

SHEET 1

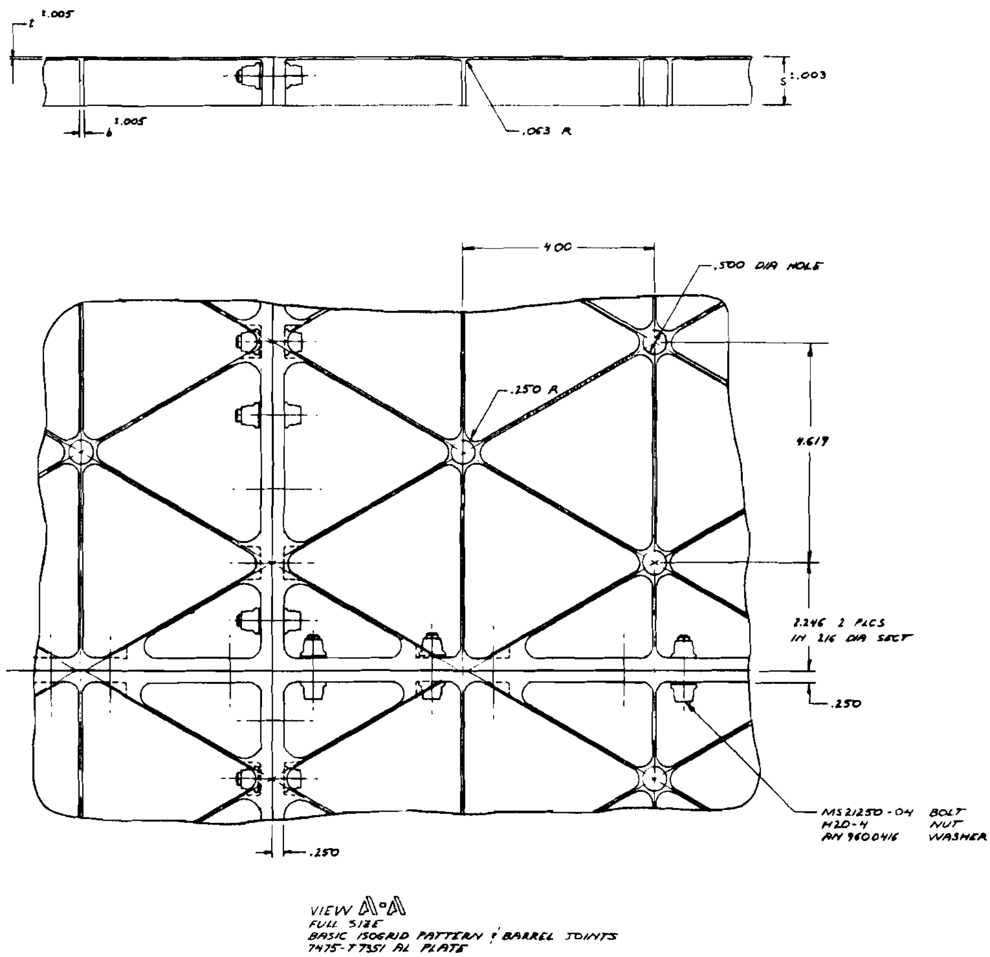


Figure 5 ISOGRID FUSELAGE SHELL STRUCTURE -- Continued

SHEET 2

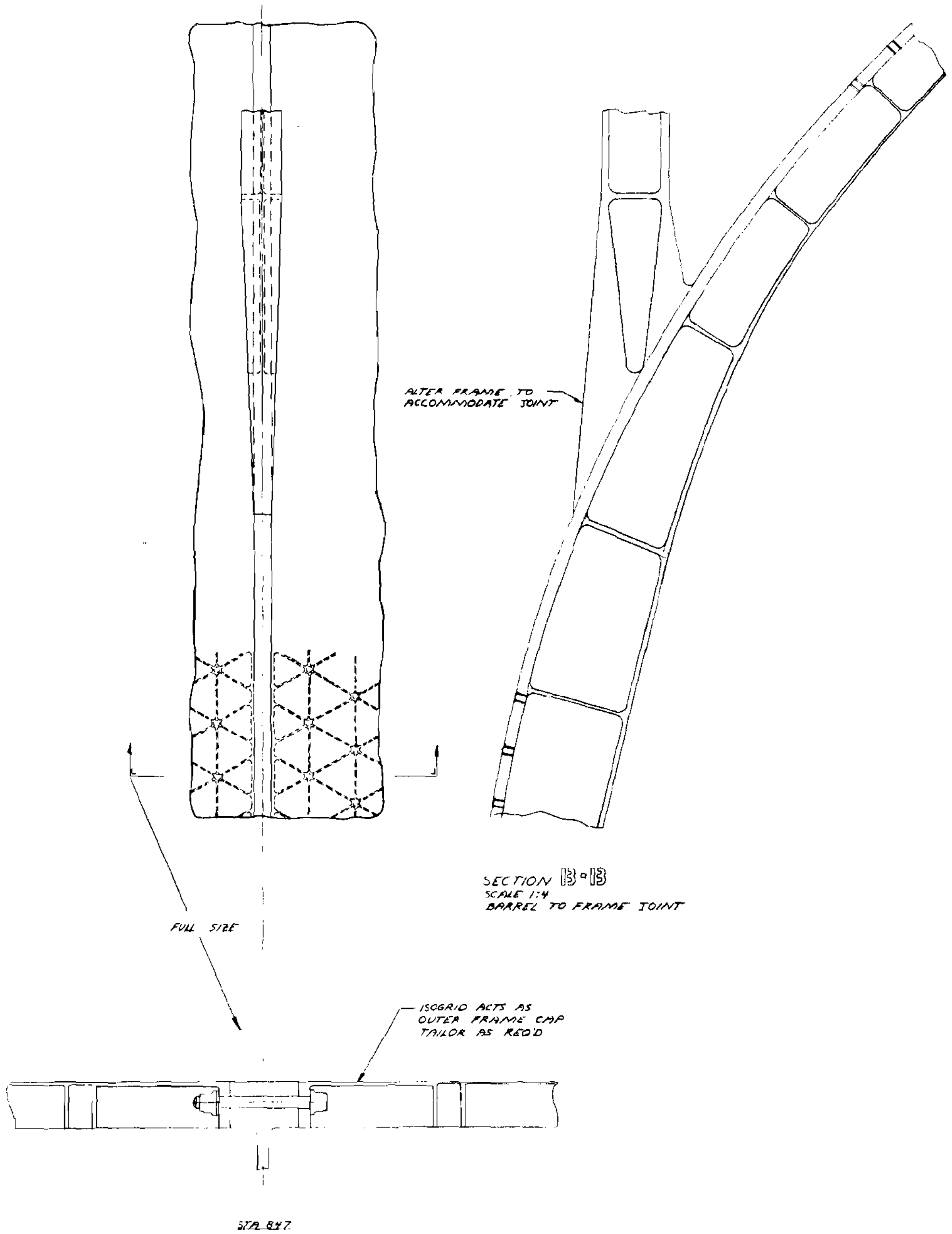


Figure 5 ISOGRID FUSELAGE SHELL STRUCTURE -- Continued SHEET 3

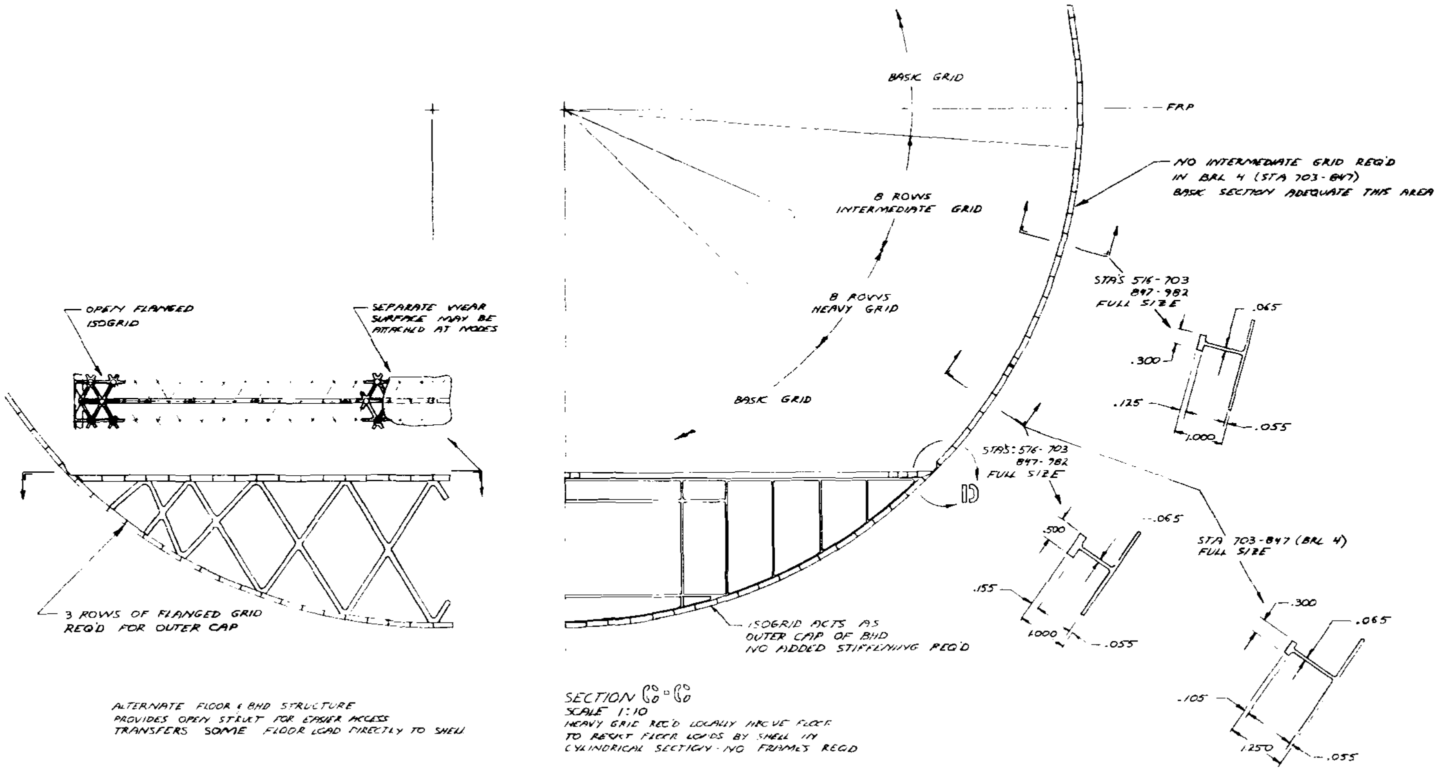


Figure 5 ISOGRID FUSELAGE SHELL STRUCTURE -- Continued SHEET 4

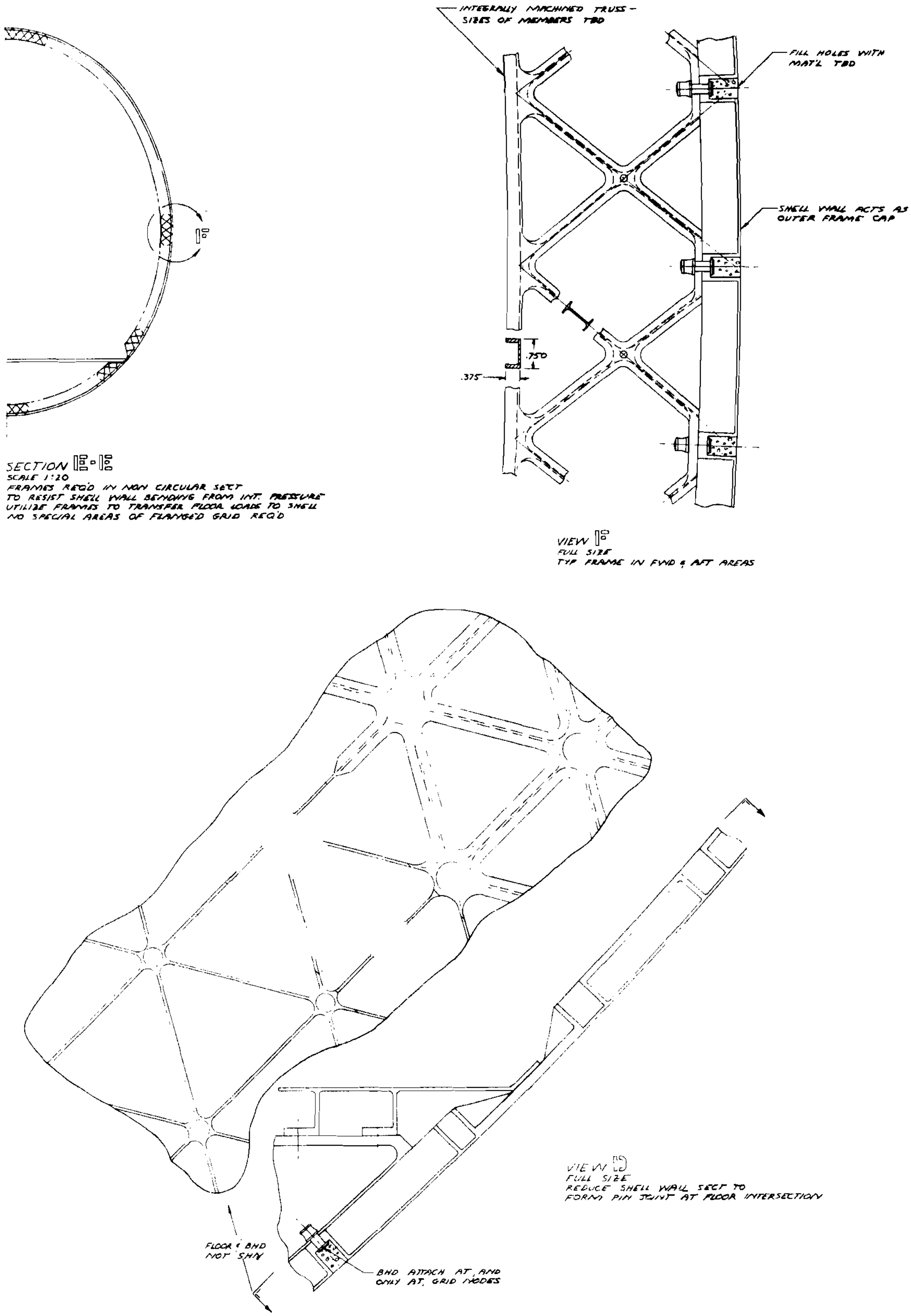
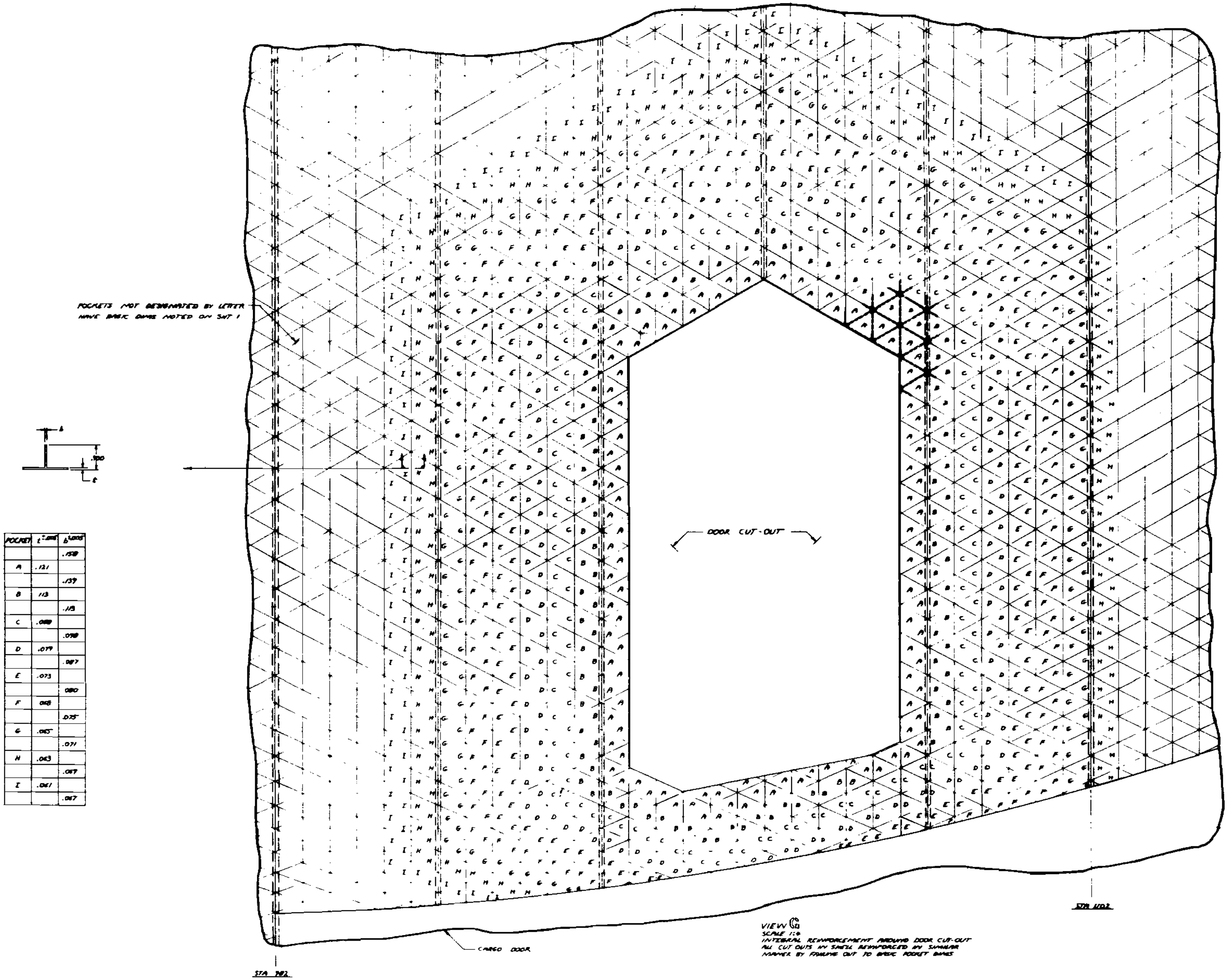


Figure 5 ISOGRID FUSELAGE SHELL STRUCTURE -- Continued SHEET 5



POCKET	t ±.005	b ±.005
		.158
A	.121	
		.139
B	.113	
		.115
C	.088	
		.098
D	.079	
		.087
E	.073	
		.080
F	.068	
		.075
G	.065	
		.071
H	.063	
		.067
I	.061	
		.067

Figure 5 ISOGRID FUSELAGE SHELL STRUCTURE -- Continued

SHEET 6

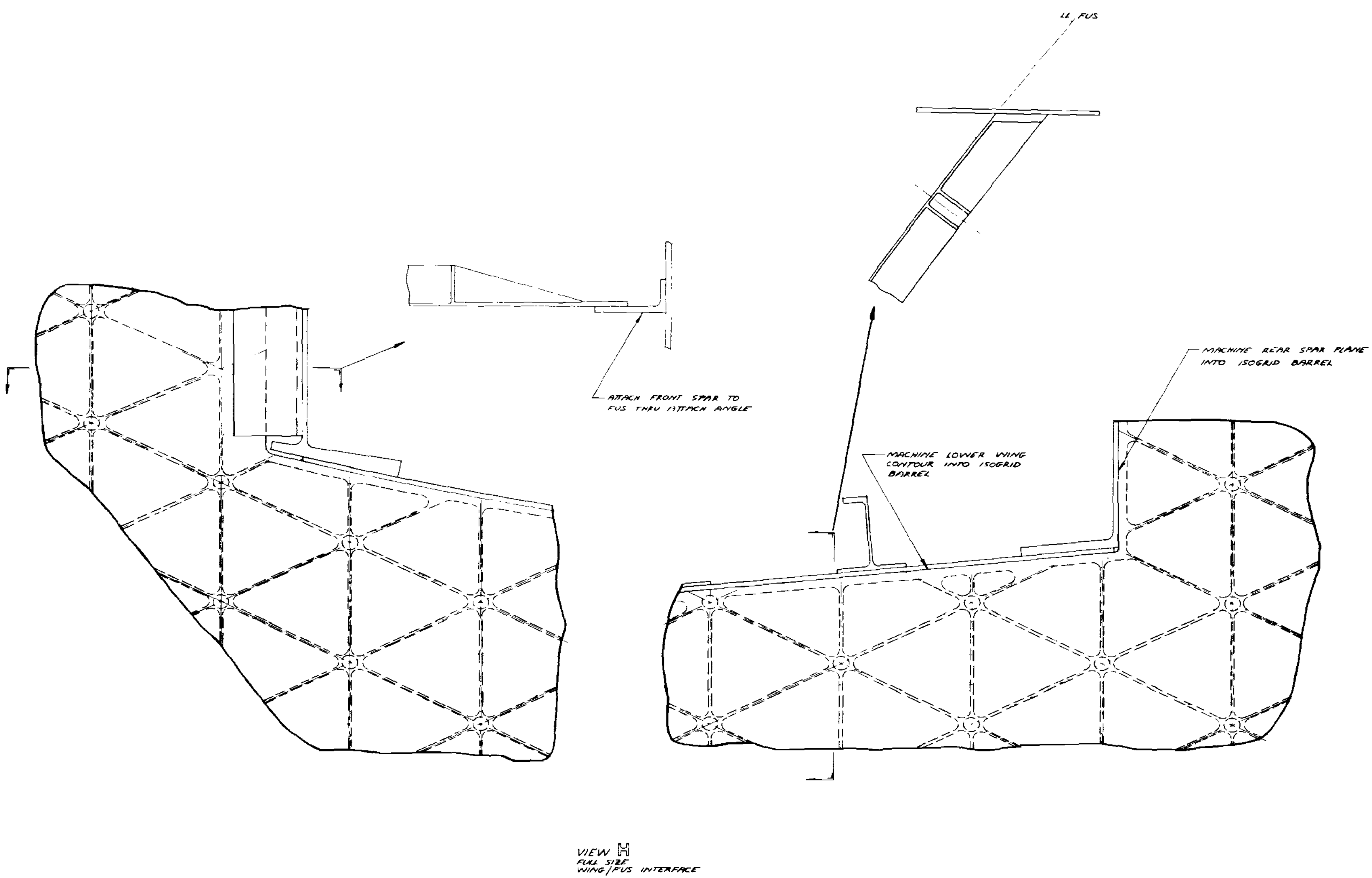


Figure 5 ISOGRID FUSELAGE SHELL STRUCTURE -- Concluded

SHEET 7

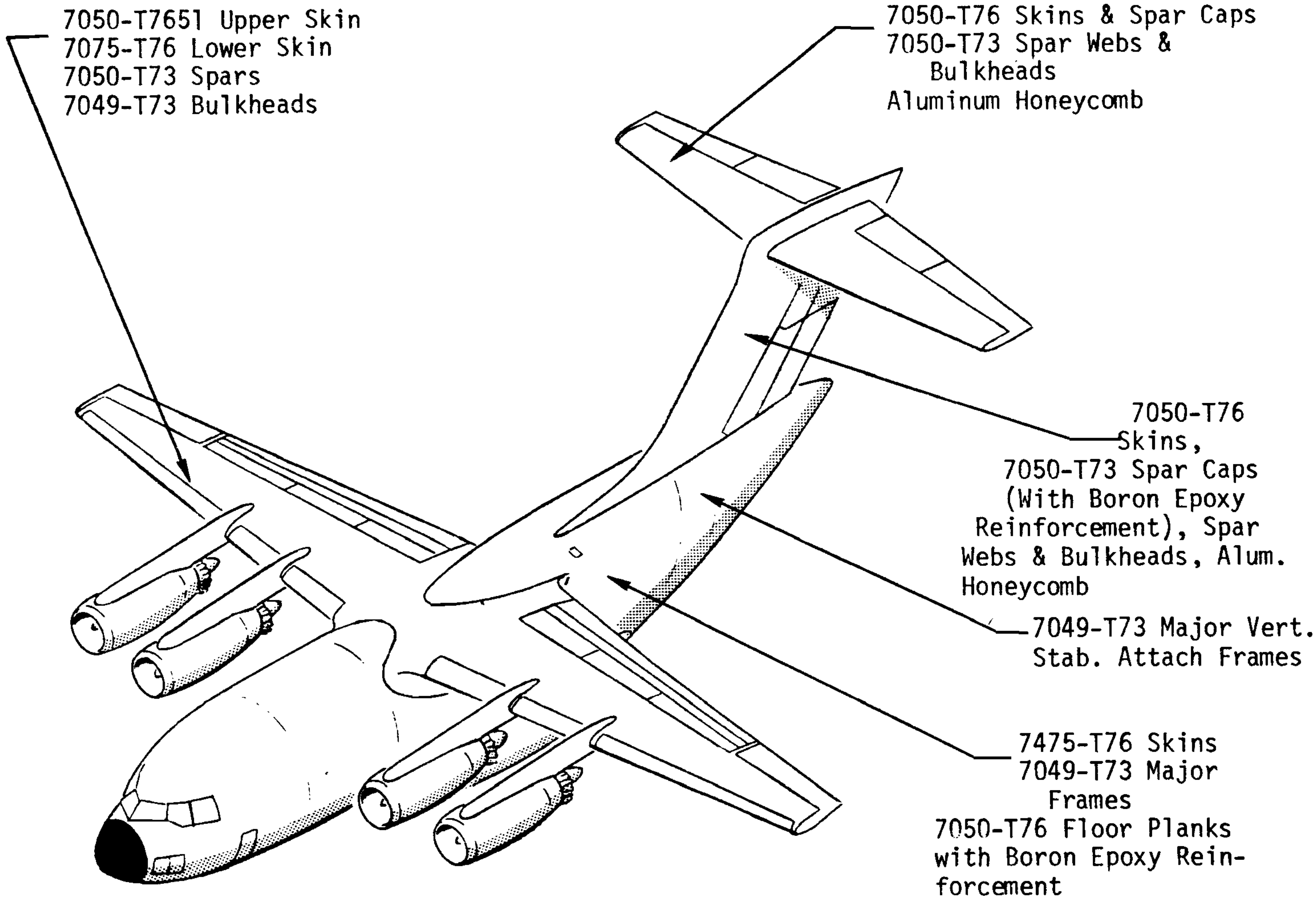


Figure 6 NEW CONCEPT AIRFRAME MATERIAL SELECTION (ISOGRID FUSELAGE)

The isogrid shell is capable of resisting bending and shear loads resulting from all flight conditions without internal frame support. However, it was assumed at the onset of this investigation that the major frames at stations 703 and 847, used in the baseline airplane to distribute wing and landing gear loads, would be required for any structural concept. Frames are also needed in the forward two barrels to resist internal pressure. This portion from stations 366 to 516 has a non-circular cross section, and internal pressure causes circumferential sidewall bending. The elimination of frames would require flanged isogrid from 2 to 2.5 inches thick. The fuselage is cylindrical from stations 516 to 900 and nearly so from 900 to 982. Internal pressure is easily resisted by hoop tension. The only other internal support structure required in this section are the floor bulkheads. They distribute the cargo loads to the fuselage under the floor and permit the floor and lower shell to act as a unit.

Floor loads can be resisted by a frameless shell by reinforcing the isogrid structure from the floor to the fuselage reference plane (FRP). The reinforcement is obtained by simple flanging of the isogrid shell (see Section C-C of Figure 5). This approach is used in the cylindrical portion where frames are not required for pressure. In the forward area, the frames which resist pressure will also distribute floor loads into the basic grid. In each case, the floor is pinned to the fuselage side wall.

The main wing is attached to the frames at stations 703 and 847 and to the skin panels in the same manner as the baseline. The fuselage penetration is accomplished by machining the rear spar plane and lower wing cutout into the shell where the wing is attached directly to the isogrid wall as shown in View H, Figure 5. The front spar is connected to the shell through an attach angle to assist assembly by preventing "shoe horning" of the wing. Pseudo-isotropic structures such as isogrid are most efficient when load paths are kept as direct as possible. Study is required to determine the best ways to carry load around or through the wing cutout area.

The baseline main landing gear attachment to struts that are integral with the frame at station 847 is considered applicable here. A reinforcing grid is required in this area to resist landing gear drag loads, although the reinforcement is not shown in Figure 5.

All door and window cutouts require integral reinforcement around the periphery. Only unflanged isogrid is required in this shell. The main jump door in the aft fuselage was chosen as the best example of cutout requirements and is discussed more fully in 3.2.2.

Frames and bulkheads required in any isogrid shell can be of the truss or shear web variety as shown in Figure 5. In these designs, the isogrid wall acts as the outer cap and may or may not require local integral reinforcement. The inner cap and web (or truss diagonals) can be machined as an integral unit. A frame or bulkhead located at a barrel interface can be attached by butt joints in the manner presented in Section B-B, Figure 5. Midspan frames or bulkheads should be attached at nodal rows as shown in View D for shear webs and View F for trusses.

Trusses are particularly suitable for the webs at these frames and bulkheads. The advantage of trusses lies in their open construction which permits penetration without special provisions. Intersecting members provide natural attach points, and the diagonals lend lateral restraint to the inner cap through torsional stiffness. A problem arises when the fuselage shell is used as the outer frame or bulkhead cap. Offset moments are induced in the curved shell requiring that it resist combined bending and axial loads. This was analyzed and shown to be feasible. The basic grid was found to be adequate as an outer cap for pressure loaded frames, both truss and web, which are attached at each node, View F, Figure 5. Actual design must consider all parameters involved, including loads, geometry, basic grid size, access requirements, etc., on a weight and cost basis.

3.2.2 Aft Section

The aft fuselage extends from stations 982 to 1437 and consists of four barrels of two segments each as shown in Figure 5. The cargo doors are considered to be attaching members and are not included in the study. This section has non-circular cross sections, so that frames are required to resist internal pressure loads. They are normal to the FRP and spaced 24 inches O.C. except in the area of the canted vertical stabilizer frames. These members attach the stabilizer through its spars in the same manner as the baseline airplane. The torque boxes at the periphery of the cargo door cutout on the baseline airplane are required on this configuration also.

The aft jump door, View G of Figure 5, is typical of any cutout in an isogrid shell. The problem of load distribution around the opening is best served by having the boundaries coincide with ribs. However, if other parameters prevail, the opening can follow any line and the grid pattern can be machined accordingly. In this case, the door sill is trimmed at the floor plane for ease of exit.

As shown in the figure, extensive integrally machined reinforcement is required around the cutout. It is heaviest around the periphery of the cutout and reduces away from the door cutout in gradually decreasing steps until it matches the basic barrel grid. Should the reinforcement extend to an adjacent barrel, it is step tapered into the basic grid of that barrel. This occurred for the jump door where the reinforcement extended into barrel 7. The reinforcing pattern was terminated at the torque box under the door. This torque box provides the required reinforcement. It should be noted that the reinforced area remains as unflanged isogrid.

3.3 PRELIMINARY DESIGN

An isogrid design proceeds in the following manner. First, the shell is sized to resist overall body loads. This analysis establishes that the fuselage will not fail in compression in any one of its three prime instability modes or in tension. Next, anomaly loads from floors, gear, wings, cutouts, etc., are defined and local beefups in the isogrid shell or substructures (such as frames) are provided to react these loads. Finally, fatigue and damage tolerance analyses are completed. One result of this procedure is that low stresses result from sizing the vehicle to the overall body loads such that fatigue and damage tolerance problems are reduced or not critical.

The designs are based on load information from the YC-15 prototype effort. Ultimate body loads, unit longitudinal loads and shear flow in the center section were determined from the envelopes of maximum bending moment, shear and torque supplemented by a critical analysis for maximum shear in barrel four. Aft fuselage body loads were taken from a YC-15 analysis which considered the effect of cargo doors and the vertical stabilizer.

Each barrel was considered separately as a complete (i.e., no cut-outs) cylinder with a radius equal to the maximum radius of the barrel. The grid elements were sized to resist failure in general instability, skin buckling, and rib crippling under combined maximum compression and shear. Optimum configurations that were designed to fail simultaneously in all failure modes required rib spacing so close and skin and rib gages so thin that they were considered infeasible from a manufacturing point of view. More reasonable sizes were derived from a quasi-optimization approach which assumed a rib spacing and plate depth and determined the skin gage and rib width by setting skin buckling equal to general instability. The ribs were then checked for crippling and increased in width if necessary.

The minimum weight configuration for any loading condition can be found by determining the element sizes for various values of plate thickness, S, at each of a number of values of rib spacing, H, as shown in Figure 7. Here the weight is expressed as a smeared thickness, $\bar{t}$. The curves presented in the Figure were constructed for the specific barrel and loading condition shown, but are representative of all barrels and conditions. Specific values depend on specific loading and barrel geometry. However, certain generalities can be made:

- There is a range of minimum weight configurations where small variations of rib spacing and plate depth produce minor changes in weight.
- Plate depth has a greater impact on weight than rib spacing.
- General instability is the dominant mode of failure in thin plates while rib crippling is critical for thick plate design.
- Skin buckling is the dominant mode for wide rib spacing, while rib crippling prevails for close spacing.

The curves in Figure 7 are based on minimum required sizes and theoretical values of $\bar{t}$. They serve to indicate the trends and establish the minimum weight zone. Past experience indicates that the minimum weight configurations of all barrels in this fuselage will fall close to this zone. Therefore, a uniform rib spacing of 4 inches over the entire fuselage will yield an efficient design that is in the realm of manufacturing feasibility and low cost.

The basic grid sizes for each barrel were determined in the same manner as outlined above, although the optimization procedure was not as extensive. Plate depths from 0.7 to 1.25 were considered for a 4 inch rib spacing. Tolerances, minimum gages, and node weight penalties were included. Manufacturing considerations resulted in a minimum skin gage of 0.040 and rib width

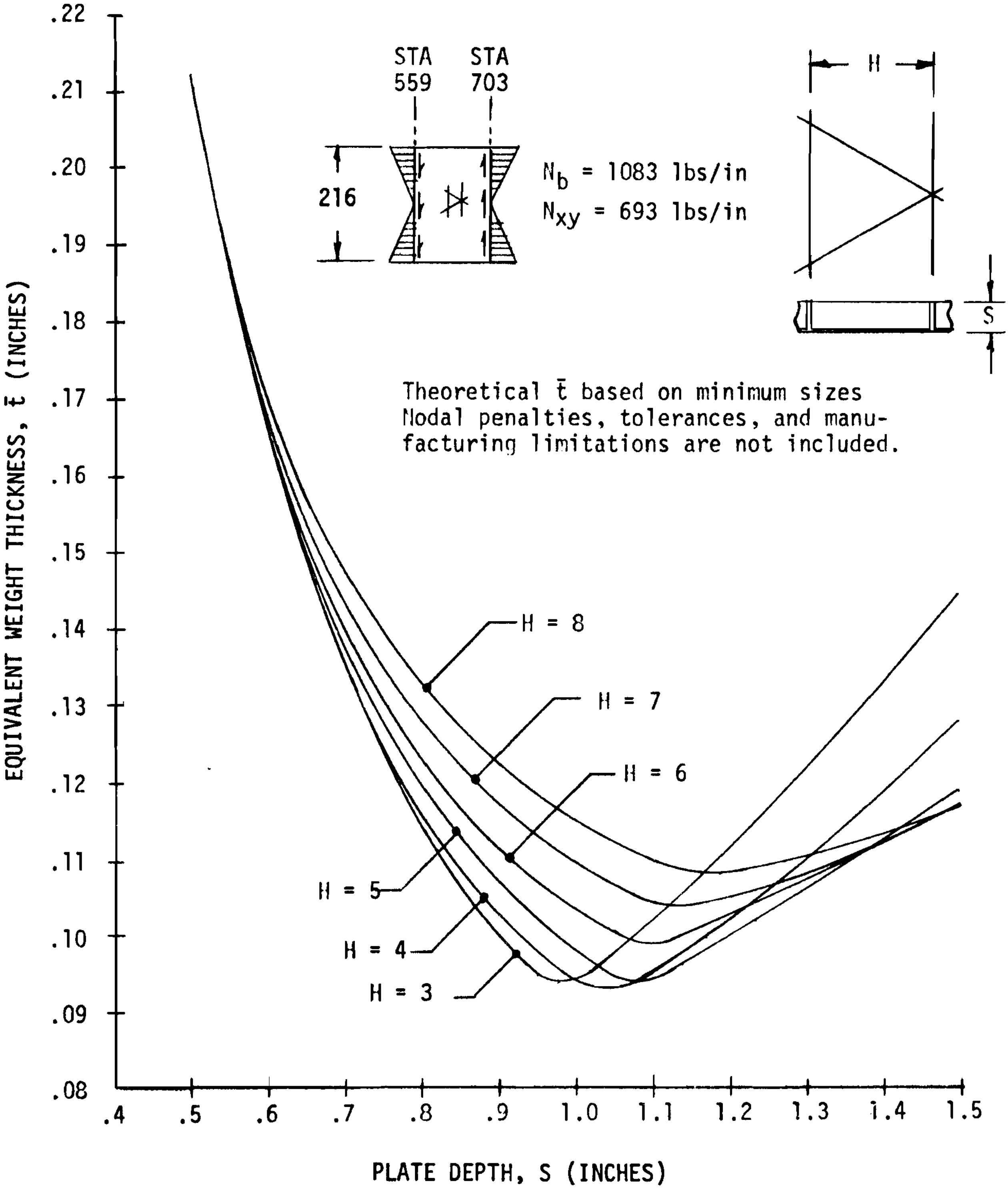


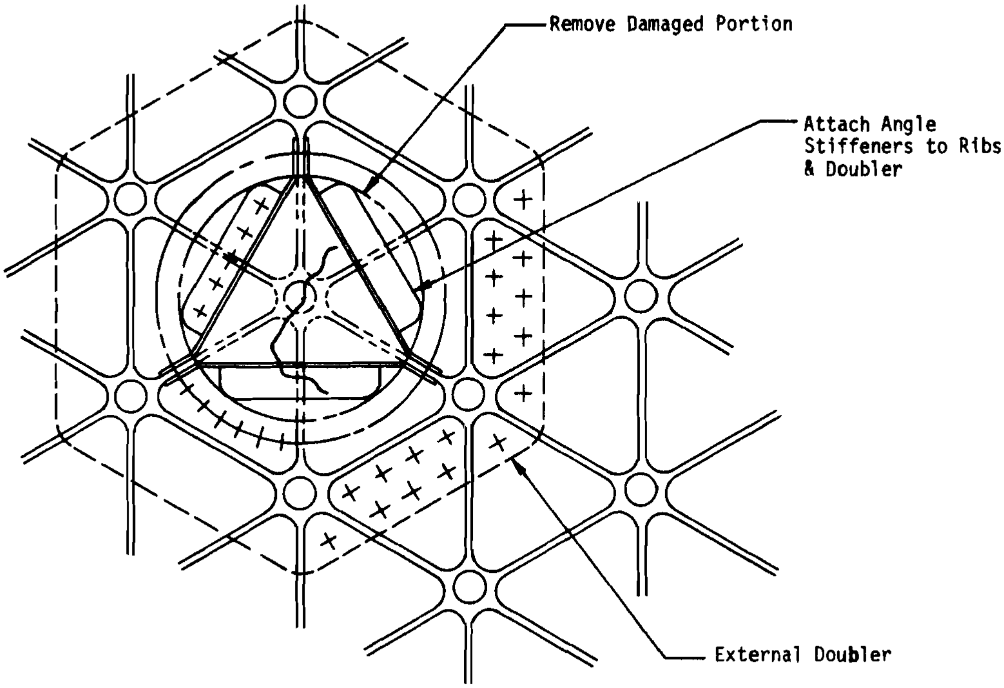
Figure 7 BASIC ISOGRID TRENDS FOR FUSELAGE SHELL

of 0.060 with ± 0.005 tolerances on each. These designs were checked for internal pressure. The non-circular barrels were analyzed as pressurized cylinders with internal frames. Shell wall bending and axial load were computed in the conventional manner. The cylindrical sections resist pressure by hoop tension. The result is that all the barrels designed for body loads resist internal pressure adequately except barrels 1, 2 and 9. The optimum plate thickness of barrel 1 is 0.8 inches for body loads and that of barrel 2 is 0.9 inches. They were both increased to 1.0 inch for pressure. The body loads in barrel 9 are so low that they were not considered, and the barrel was designed for pressure.

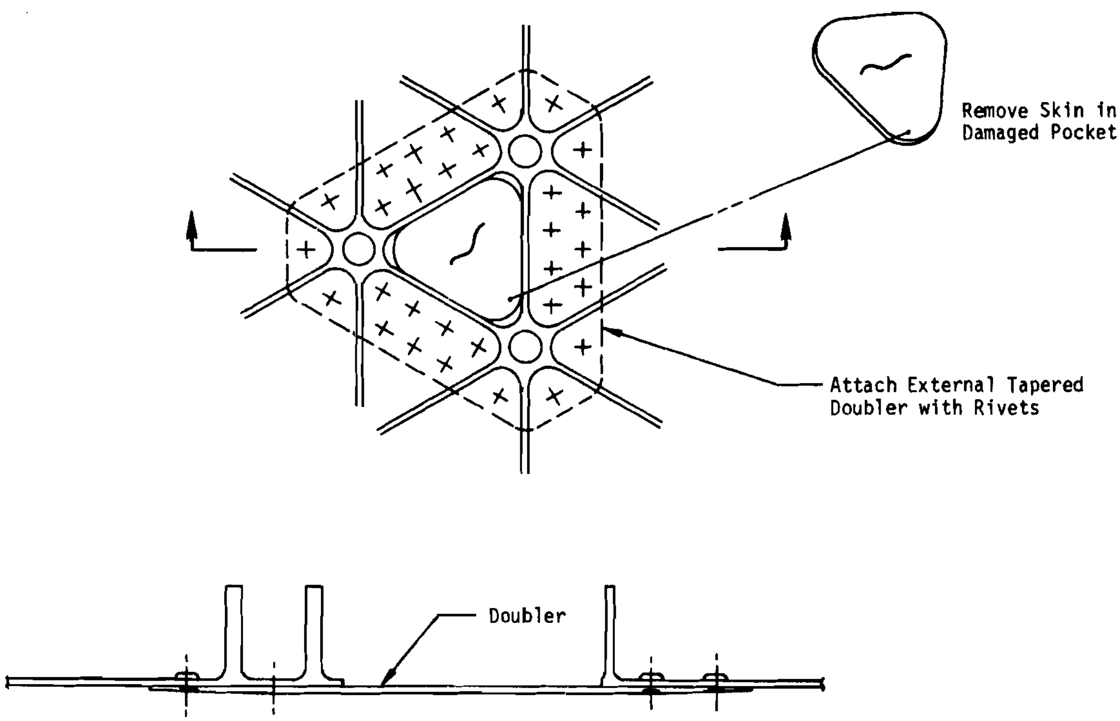
Integral reinforcement around cutouts was treated as a stress problem. The openings were assumed to be holes in infinite plates and the sizing was performed by the method recommended in Reference 1. The flanged isogrid reinforcement required by the floor loading was determined by treating the sidewall as a smeared out frame. The grid was sized to resist the frame moments (per inch) of the sidewall in the conventional manner. The final analyses are discussed in Section IV.

3.4 REPAIR TECHNIQUES

Experience in repairing isogrid structure is available from the McDonnell Douglas Delta, space vehicle shroud, and Orbital Workshop space vehicle programs. Typical examples of preliminary repair methods are shown in Figure 8. Attached stiffeners and doublers are either bonded to the isogrid or are attached with mechanical fasteners. Ribs which are deformed in brake forming can be either straightened easily with simple hand tools or can be "bridged" with doublers. No difficulties have been encountered with repaired isogrid structure to date. Isogrid is "forgiving" since it possesses essentially two load paths, i.e., skin and ribs. Additional development of repairs for aircraft are needed, however, to restore fatigue life and complete integrity for all types of loadings in shell structure.

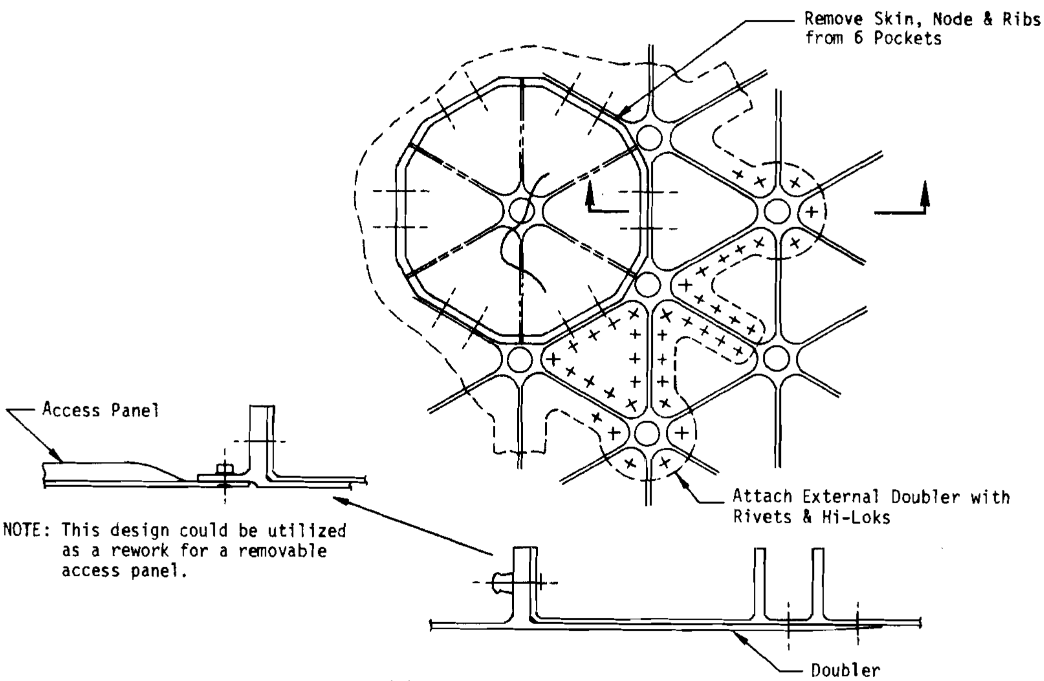


(a) SKIN NODE & RIB DAMAGE

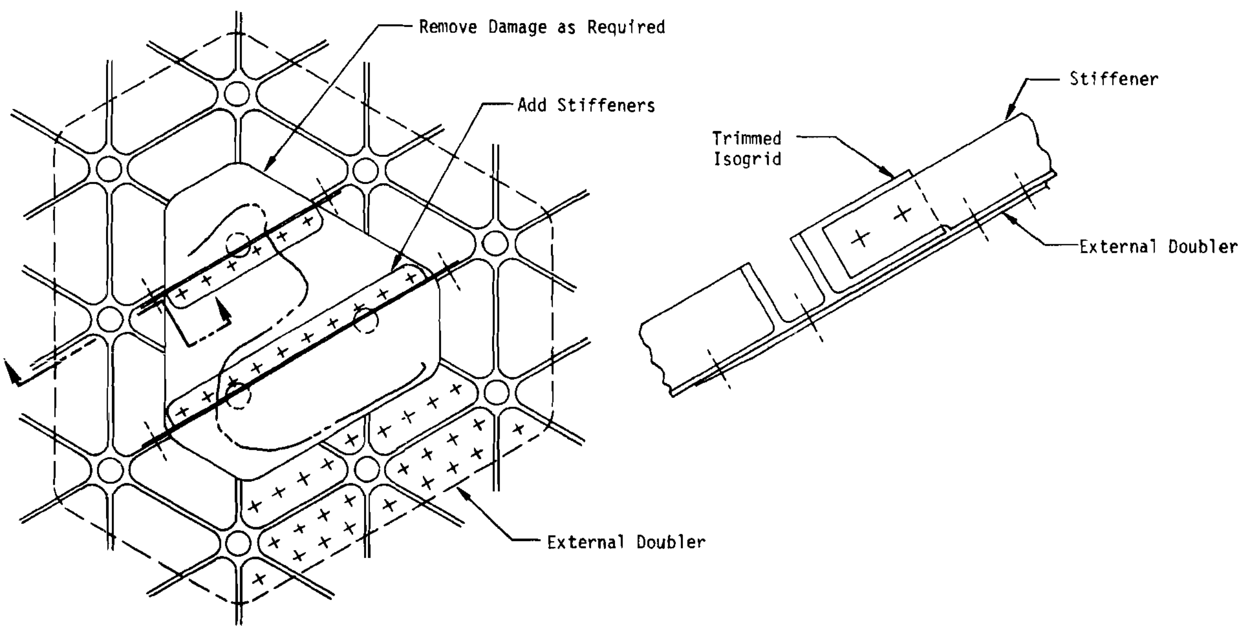


(b) SKIN DAMAGE - ONE POCKET

Figure 8 ISOGRID REPAIR CONCEPTS



(c) SKIN, NODE & RIB DAMAGE



(d) MORE EXTENSIVE SKIN, NODE & RIB DAMAGE

Figure 8 ISOGRID REPAIR CONCEPTS -- CONCLUDED

SECTION IV

STRUCTURAL ANALYSIS

The results of a preliminary structural analysis of the isogrid concept as applied to the STOL fuselage is summarized in this section. Detailed structural analyses data are found in Reference 2. Fatigue, damage tolerance and ultimate strength analyses were performed to support and verify the structural design described in Section III.

Typical minimum margins of safety and associated design stress levels for the more highly loaded Barrel 5 section are summarized in Figure 9. These margins are for compression, (general instability, local skin buckling and rib crippling), fatigue and damage tolerance. The minimum margin is for general instability failure. The fatigue and damage tolerance margins are high because of the low stress levels inherent in isogrid construction (required for general instability).

The analyses demonstrate that an isogrid fuselage is feasible for the AMST airplane. For more complete structural optimization and associated weight benefits, additional detailed analyses are required.

4.1 FATIGUE

The fatigue analysis was based on use of the ground-air-ground (GAG) cycle, which has been demonstrated to cause 80% or more of all fatigue damage for the AMST. The basic data to generate the GAG spectra are in Volume I where the incremental load factor (Δn) occurrences for each flight mission are identified. Integration of these data as C.G. load factor exceedance spectra are shown in Figure 10. This figure defines the average GAG $\pm$ load factor excursion per design lifetime for the fuselage. The associated design frequency is four times the number of landings per service life of 15,000 hours that the aircraft will make or 4 x 23755 = 95020 landings (Volume I). On the basis of one GAG cycle per landing the number of GAG cycles was then equal to 95,020. In the longitudinal direction both inertia and pressure loads were included in the GAG cycle. For the hoop direction the GAG cycle consisted only of pressure loads.

The fatigue GAG damage D_R was calculated using linear damage theory. The allowable service life capability then is defined as follows:

$$\text{Allowable service life} = \frac{60{,}000}{4} \; \frac{1}{D_{R/K}} = \frac{15{,}000\ K}{D_R} \qquad (1)$$

Where K = factor representing fraction of total damage due to GAG

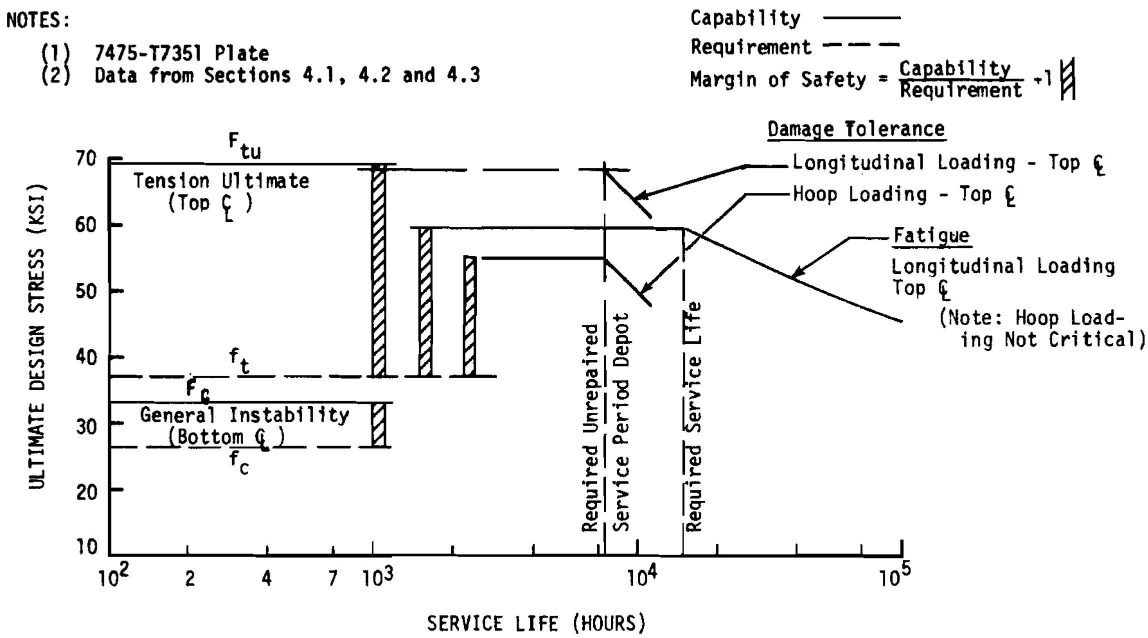


Figure 9 CRITICAL INTEGRITY MODES FOR ISOGRID FUSELAGE BARREL #5

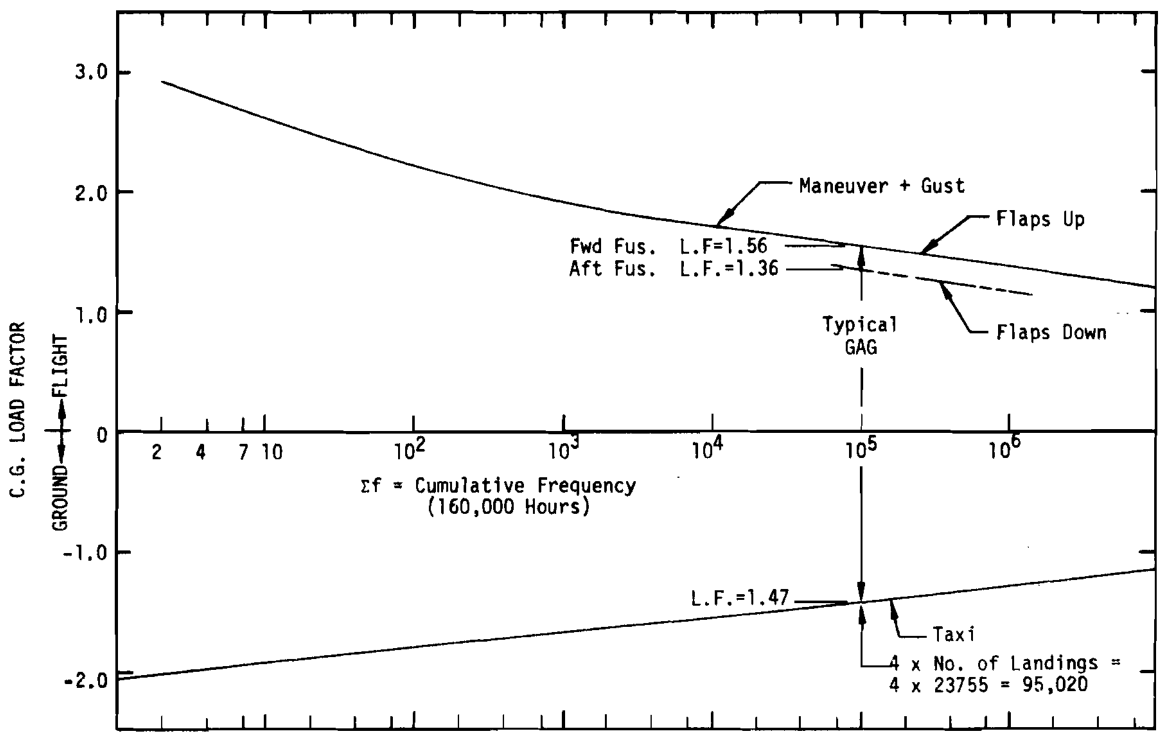


Figure 10 C.G. LOAD FACTOR EXCEEDANCE SPECTRA

Fatigue checks were made as follows:

1. Those due to longitudinal loads at Stations 439 and 703 forward of the wing, and at Stations 847 and 982 aft of the wing,
2. Those due to hoop loads at a selected critical station, and
3. A preliminary check of the butt splice configuration.

The steps in each analysis included:

1. Definition of the GAG load factors/pressure schedule,
2. Derivation of one "g" stresses for each of the flight missions, and
3. Computation of the damage.

Required basic data included:

1. The C.G. load factor exceedance spectra, Figure 10
2. One "g" bending moments, Reference 3
3. S/N data for basic structure, Volume I

4.1.1 Fatigue Due to Longitudinal Loads

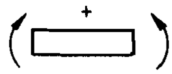
The typical load GAG cycle for Stations 439 and 703, forward of the wing is 1.56g's flight and 1.47g's ground taxi, (Volume I, Figure 11). The typical GAG flight load for stations aft of the wing (847 and 982) result from a flap extended condition. The aircraft flies less than 10% of the time with flaps down, hence the typical flight g level of the GAG cycle is only 1.36g's rather than 1.56g's. The ground taxi g level remained unaltered.

One "g" bending moments are presented in Reference 3 for Stations 725 and 871. The dead weight elements were extended in a rotational manner to the four selected stations. Stations 847 and 982 are also loaded by an average one "g" flaps down balancing tail load (BTL) of 14,000 lbs. The resulting total one "g" bending moments are shown in Table III.

A similar set of moments were computed for the taxi condition, those involving nose gear loads, as well as inertia loads, Reference 2. Both flight and taxi bending moments were changed to stresses using the appropriate GAG load factors and the section properties from the detailed analysis (Reference 2). Pressure stresses corresponding to the airplane and cabin altitudes reached during each mission (Reference 4) were defined and added to the flight condition stresses. The required number of GAG cycles for each mission was taken as four times the associated number of service life landings, Reference 3. These data, along with the S/N curves for basic structure were inputs for the fatigue checks.

These analyses showed that the margins of safety in fatigue under longitudinal loading were high. Sample calculations for the most critical Station, 847, are shown in Table IV.

TABLE III FUSELAGE ONE "g" FLIGHT BENDING MOMENTS

BENDING MOMENT (10^{-6}) IN.-LBS 

MISSION*	FUSELAGE STATIONS			
	439	703	847	982
1(O)	-2.172	-5.570	-19.253	-13.745
1(R)	-2.177	-5.585	-19.253	-13.745
2(O)	-2.719	-6.973	-19.633	-13.987
2(R)	-2.727	-6.988	-19.633	-18.987
3	-1.214	-3.114	-18.314	-18.152
4	-2.177	-5.585	-19.253	-13.745
5	-1.222	-3.133	-18.319	-13.152

*(O) Outbound; (R) Return

TABLE IV SAMPLE FATIGUE CALCULATION FOR STATION 847

MISSION	σ_{MAX} (KSI)	K	N_i** (CYCLES)	n_i° (CYCLES)	ΔD_R $^{\Delta}$
1(O)	19.0	0.36	$3.0(10^6)$	30,480	0.0191
1(R)	19.3	0.35			
2(O)	19.0	0.37	$3.1(10^6)$	9,144	0.0057
2(R)	19.2	0.37			
3	19.2	0.32	$2.8(10^6)$	764	0.0004
4	12.6	0.54	$>10^7$	17,296	0.0017
5	16.0	0.38	$>10^7$	37,336	0.0060
				TOTAL	0.0329

*(O) Outbound; (R) Return; **2024-T3 S/N Data

°4 Times No. of landings; $^{\Delta}\Delta D_R = n_i/N_i$

$$\text{Allow Life (Hours)} = \frac{60{,}000}{4}\;\frac{1}{D_R/0.8} = \frac{15{,}000(.8)}{0.0329} = 0.36(10^6)$$

NOTE: 0.8 is factor since GAG is only 80% of damage.

4.1.2 Fatigue Due to Hoop Loads

Longitudinal cracks are caused by pressure stresses. Only one check for hoop direction loadings was required at a minimum gage section. The minimum gage is in barrel 1, which has an effective thickness of 0.054 inches, giving pressure stresses of $\Delta p \times 108/.054 = 2000\ \Delta p$. The Δp's are the same as those used in the longitudinal case condition. The fatigue life computation procedure follows that of Table IV. For this case, R equals zero, the damage (D_R) is 0.0399, and the allowable life is 0.38×10^6 hours. It follows that heavier gage areas will have better fatigue life.

4.1.3 Fatigue at Splices

A preliminary analysis was made of the fatigue properties of the butt splice proposed for the isogrid structure as shown in Figure 11.

Experience has indicated that bolt fatigue is not a problem if the bolt stress level is less than 0.8 F_{ty}. The MS 21250-04 bolts have a F_{ty} of 163 KSI. Hence, acceptable life exists if the bolt stresses are less than 130.4 KSI. Ultimate bolt stresses are less than this allowable, so no bolt fatigue problem exists. The splice design itself resembles typical "bathtub" fitting designs which have demonstrated satisfactory service life. However, test data is required to verify or further develop this approach.

4.1.4 Fatigue Under Acoustic Loads

The acoustic fatigue environment for the STOL fuselage is found in Volume I. The critical environment for the fuselage is in Zone F2, as shown in Figure 12. The minimum isogrid skin gage in this area is 0.04 inches (minimum tolerance on $0.045 \pm .005$ inch dimension). Current in-house acoustic fatigue charts pertain only to rectangular panels. Hence, the size of an equivalent square panel which had the same natural frequency as the isogrid panels was determined.

The relative frequencies of triangular and square plates are shown in Figure 13. The isogrid triangle height (h) is 4.0 inches. The square plate dimension (a) with equivalent natural frequency is 3.24 inches with simply supported edges, and is 3.14 inches with fixed edges. An everage of 3.19 inches was selected.

An acoustic fatigue check of this equivalent 0.04 inch thick square plate, showed that the damage per design lifetime was slight so that this mode is not critical.

4.2 DAMAGE TOLERANCE

The damage tolerance analysis follows the general procedure outlined in Volume I, Section 7.2. That section contains a compilation of the crack growth rate (da/dn) versus stress intensity factor (ΔK) data that are used in the damage tolerance checks. Both hoop and longitudinal cracks were considered at the four check stations (439, 703, 847 and 982) and critical stations were chosen for one hoop crack and one longitudinal crack damage tolerance analysis. The

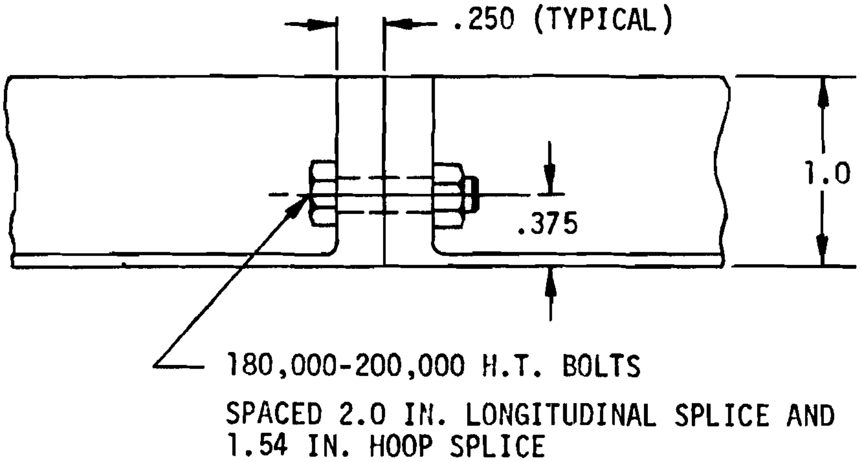


FIGURE 11 TYPICAL SPLICE IN ISOGRID
FUSELAGE SHELL STRUCTURE

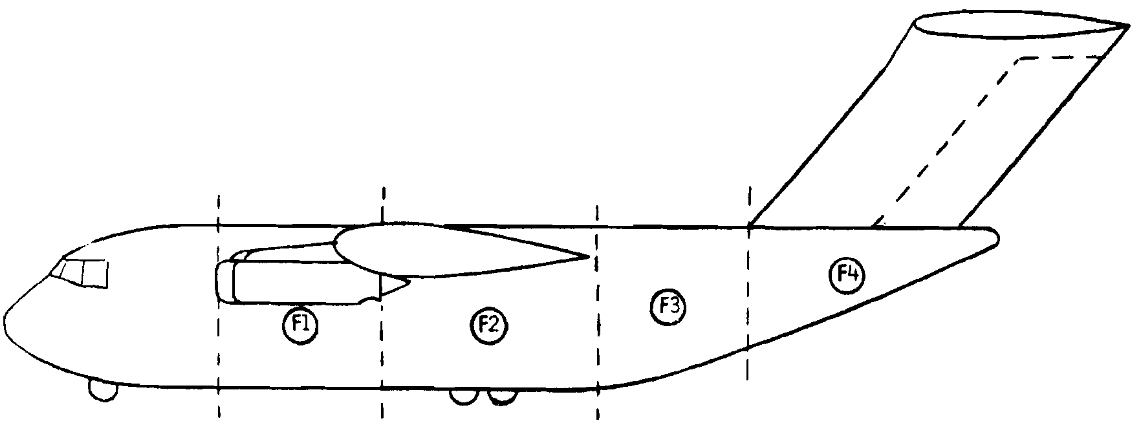


FIGURE 12 ZONES OF ACOUSTIC NOISE ON FUSELAGE

two analyses were both for surface flaws (a = .125 inches) in the basic structure. These flaws were kept 24 inches away from any joints to negate edge effects. No damage tolerance checks were made at the joints. (The joints would be developed using analysis and test data such that their damage tolerance would be equal to or better than the surface flaw.)

4.2.1 Damage Tolerance for Longitudinal Loads

The fuselage damage tolerance analyses were developed from a spectra based on a consideration of the following loading modes.

1. Taxi environment,

2. Flight maneuver environment,

3. Low level maneuver plus gust environment,

4. A cabin pressurization environment, and

5. A flaps down loading for the aft fuselage.

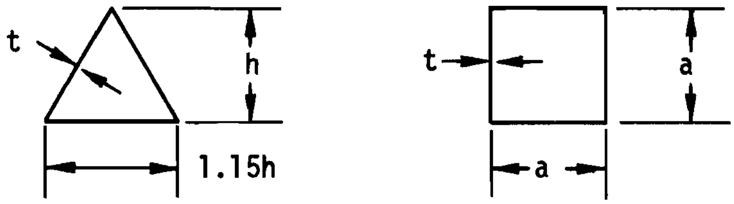
This preliminary work established that only the taxi and low-level-maneuver plus gust modes were significant enough to be included in the spectra. The taxi and maneuver plus gust spectra were examined at the four check stations. The critical spectra were at Station 847, Reference Table V. This station, therefore, was selected for the analysis.

The Table V spectra development procedure paralleled the example presented in Section 7.2.1.2 of Volume I. The initial crack was an a = 0.125 inch surface flaw on the fuselage top centerline and located 24 inches aft of Station 847. The applicable inspection periods are those associated with special visual and depot periods. Depot inspection resulted in the highest design allowable stress (50,100 psi) for the 7500 hour minimum period of unrepaired service usage and a + 0.36 margin of safety relative to the maximum ultimate bending plus pressure stress of 36,900 psi for the selected design.

4.2.2 Damage Tolerance for Hoop Loads

Longitudinal cracks result from fuselage pressurization stresses which are maximum in minimum gage areas. The minimum effective thickness (t_{eff}) is 0.054 inches and exists on the top of barrel 5. Therefore, this area was selected for analysis.

The flight profile data (Volume I) show that pressurization occurs in all missions except mission 4. This results in a total of 19,431 pressurization cycles per service lifetime. The operating pressure differential is 7.5 PSID which was conservatively assumed to exist during each flight. Hence, the design spectrum is



ω (CPS)	$\frac{\gamma}{h^2}\left(\frac{3860\ D}{t}\right)^{1/2}$	$\frac{\gamma t\ (10^4)}{a^2}$
γ(SIMPLE SUPPORT)	4.77	19.2
γ(CLAMPED)	9.23	35.01

FIGURE 13 NATURAL FREQUENCIES OF ISOGRID AND SQUARE PANELS

TABLE V HOOP CRACK LOAD SPECTRA FOR STATION 847

SPECTRUM	n_i (CYCLES)	$\Delta\sigma$ (KSI)	R
LOW LEVEL MANEUVER + GUST	0.90 (10^6)	4.1	+0.47
TAXI	0.47 (10^6)	3.2	+0.56

$$\Delta\sigma = \sigma_{press} = Pr/t_{eff} = 15{,}000 \text{ PSI} \qquad (2)$$

$$R = 0$$

$$n_i = 19{,}431 \text{ cycles/15,000 hours}$$

The initial crack was again an a = 0.125 inch surface flaw. The safe crack growth period characteristics in conjunction with the special visual and depot inspectability period requirements defined a design allowable stress of 54,400 PSI for the 7500 hour depot minimum period of unrepaired service usage. This compares to the maximum ultimate stress of 36,900 PSI for the selected design, giving a + 0.47 margin of safety. (Principal stresses at the side quadrant are not critical since the maximum tail load is 8,750 lbs.)

4.3 ULTIMATE STRENGTH

Isogrid consists of a rib grid arranged as equilateral triangles on a facing sheet. This structure has equal bending stiffness in all directions. Hence, it resists load exactly like an isotropic sheet except that it has significantly increased bending stiffness on an equal weight basis. This inherent distributed stiffness allows construction of a fuselage shell with few or no frames. For the AMST aircraft, frames are required only at the front and rear spars and at the fuselage out-of-round areas.

The ultimate analysis methods for isogrid are based on the work reported in Reference 1 which shows that isogrid acts like a buckle resistant monocoque shell with a large effective skin thickness and a reduced modulus of elasticity. Because of this distributed property characteristic, the isogrid shell is sized to the overall applied distributed loads. The isogrid shell so sized is then modified to support the anomaly loads from floors, floor beam trusses, out-of-round fuselage, shear concentrations under the wing, etc. The analysis techniques used in these steps require relatively simple equations to derive applied forces, member stresses, and compression instability capabilities.

In areas of major discontinuity, loads over and above the overall distributed loads are induced. In the baseline fuselage, these major discontinuity areas are at the wing box, the gear attach, and around the rear door. The baseline stringer-skin fuselage includes structural provisions to carry longitudinal loads around the wing cutout. This is undesirable in an isogrid fuselage since high concentrated local compressive stresses aggravate the general instability problem. It is, therefore, desirable to provide continuity through the wing box by means of two ribs aligned with the fuselage shell. This approach minimizes the effects of this discontinuity.

The baseline fuselage provides frames and heavy skins to distribute and resist the gear loads. The isogrid shell concept similarly provides local frames and heavier isogrid to distribute and resist the gear loads.

The third major discontinuity area is associated with the large aft door. A recognized problem is shear concentration at the corner of the door in the fuselage area forward of Station 982. Based on loads from the discrete element analysis of the baseline fuselage in this area, reinforcements were provided in the isogrid fuselage.

The floors and floor beams introduce additional local shears, torques and bending moments into the fuselage shell wall. Computer programs are available to determine these loads and the required stress analysis relationships are defined in Reference 1. These loads are all resisted by a local distributed stiffening of the isogrid shell. This stiffening can be achieved by thickening the skin, by heavier ribs, by capping the ribs, by a deeper section, or by combinations of any of these approaches.

4.3.1 Ultimate Strength for Overall Distributed Loads

The overall distributed fuselage loads (given in Volume I) include envelopes of maximum ultimate vertical and lateral loads. The isogrid fuselage, currently designed, can resist the maximum moment/shear/torque combination applied in any section orientation through the full 360°. This means that the lateral loads do not have to be considered, since they are less in magnitude than the vertical loads.

The fuselage is divided into barrels of discrete length. The maximum vertical load envelopes were examined and all critical load conditions for each barrel were tabulated. Then, the original load runs were examined; and compatible shears, moments and torques were compiled for each of these conditions. The fuselage barrel was checked for these conditions for general instability, skin pocket buckling and rib crippling. No tension checks are required since the ultimate tension stresses approximately mirror the ultimate compression stresses, and the compressive stresses are all low relative to the tension ultimate.

4.3.1.1 General Instability - The equations for general instability capability are based on the data in Reference 1 and on in-house unpublished data. The approach computes the compression, shear and torque panel loading capabilities (N_{CR_B}, N_{CR_S}, and N_{CR_T}) in terms of the section moment, incremental moment and torque (M, ΔM, T) respectively, considering the basic shell properties (R, t^*, E^*, L) as shown in Figure 14.

The isogrid shell sections were analyzed by calculating the allowables and then, using the applied loadings and an applicable interaction equation to obtain the margins of safety. The equations used are summarized in Table VI. The shear factor and its use in the shear buckling equation is taken from Figure 15. The critical spot was determined to be in barrel 5 for which the conditions considered and the resulting margins of safety are shown in Table VII. The margins are relatively high because of section minimum gauge constraints.

4.3.1.2 Local Skin Buckling - The skin pockets between the ribs were designed to be buckle resistant. The top and bottom centerline skin pockets were checked for bending plus torque loads, the side centerlines for torque plus shear loads. The pertinent equations are shown in Table VIII. The minimum margin of safety for this analysis, in barrel 3, was +0.58.

4.3.1.3 Rib Crippling - Rib stability under compressive loadings was also analyzed. As with the skin buckling, the ribs at the top and bottom centerlines were checked for bending and torque loads, and the ribs at the side centerlines for torque plus shear loads. The pertinent equations are shown in

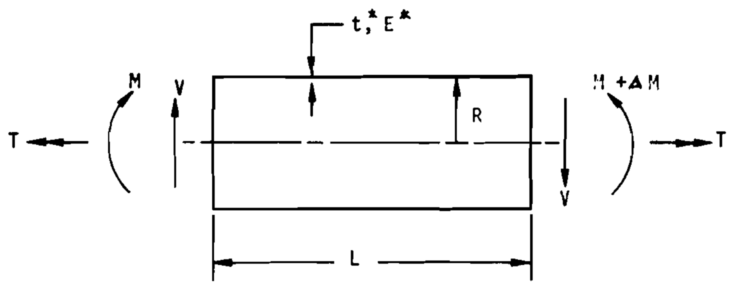


Figure 14 LOAD MODEL FOR GENERAL INSTABILITY

TABLE VI GENERAL INSTABILITY ANALYSIS EQUATIONS		
FUNCTION		EQUATION
SHELL GEOMETRY		R, t, E, L (Figure 14)
EQUIVALENT SHELL PROPERTIES (REFERENCE 1)		$t^* = t\left(\frac{\beta}{1+\alpha}\right)$ $E^* = E\left(\frac{(1+\alpha)^2}{\beta}\right)$
BUCKLING ALLOWABLE (REFERENCE 1 & UNPUBLISHED DATA)	BENDING	$N_{cr}(B) = 0.397\ E^*\ (t^*)^2/R$
	SHEAR+	$N_{cr}(S) = 0.612\ \gamma_v\ E^*(t^*)^2/R$
	TORQUE	$V_{cr}(T) = \frac{0.5\ E^*\ t^*}{(R/t^*)^{1.25}(\ell/R)^{0.5}}$
LOADS	BENDING	$P_B' = (MYt_{eff})/I$ (#/in)
	SHEAR	$P_S' = (\Delta MYt_{eff})/I$ (#/in)
	TORQUE	$P_T' = T/2A$ (#/in)
LOAD RATIOS	BENDING	$R_B = P_B'/N_{cr}(B)$
	SHEAR	$R_S = P_S'/N_{cr}(S)$
	TORQUE	$R_T = P_T'/V_{cr}(T)$
INTERACTION (REFERENCE 4)		$R_B + R_S + (R_T)^2 \leq 1.0$

+See Figure 15 for γ_v

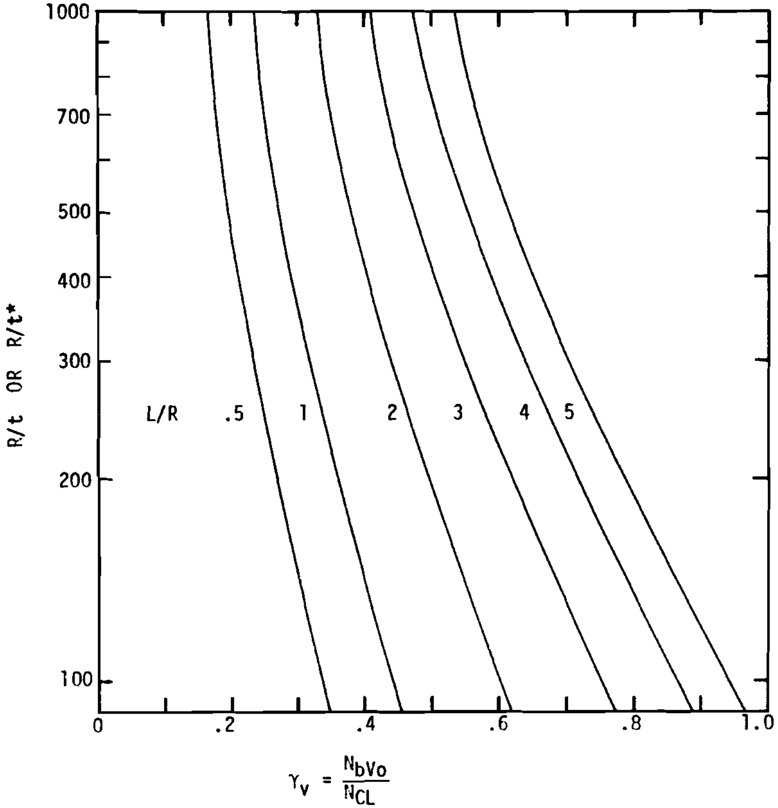


Figure 15 ISOGRID SHEAR FACTOR FOR GENERAL INSTABILITY MODE

TABLE VII SUMMARY OF BARREL #5 INSTABILITY ANALYSIS

LOADING CONDITION *		MARGIN OF SAFETY
NAME	COMMENT	
-ONE "g" BALANCED MANEUVER	MAXIMUM ULTIMATE POSITIVE BENDING MOMENT	+4.88
UNCOORDINATED ROLL	MAXIMUM ULTIMATE TORQUE - STA 870 TO 982	+1.85
LATERAL DRIFT LANDING	MAXIMUM ULTIMATE TORUQE - STA 847 TO 870	+1.08
2-POINT 4.63° TAIL DOWN LANDING	MAXIMUM ULTIMATE NEGATIVE SHEAR	+1.50
2-POINT 3.80° TAIL DOWN LANDING	MAXIMUM ULTIMATE NEGATIVE BENDING MOMENT	0.71

NOTE: * These are external fuselage load conditions, see Volume I, Section II.

Table IX. As is usually the case, rib crippling is not a stress problem. The minimum margin of safety, in barrel 3, is +4.26.

4.3.1.4 Hoop and Longitudinal Splices - Butt type splices were proposed for the isogrid fuselage, wherein the edges of the isogrid sheets were designed with integral attach flanges as shown in Figure 5, sheet 2. The hoop splices are located between each barrel and longitudinal splices are at the top centerline and at 120° to each side of this centerline. Only one type of bolt and two bolt patterns are used. The bolts proposed for all splices are MS 21250-04, 180 KSI heat treat, which are spaced 1.54 inches on center in the hoop splices, and 2.0 inches on center in the longitudinal splices.

The hoop splices were checked at the top or bottom centerline, where axial loads from the bending moments and cabin pressure combine with torque shears; and at the neutral axis of the cross section, where axial loads from the cabin pressure combine with shear and torque loads. The longitudinal splices 120° from the top centerline, which are loaded by tension from the cabin pressure, shear and torque loads, and the bending moments up the side of the fuselage from the floor loads were also checked. A summary of loading conditions considered for hoop and longitudinal splices appears in Figure 16.

For the longitudinal splice analyses, both overall distributed loads (developed for the instability checks) and floor loads were considered. Unlike the baseline, where the floors are tied into frames which then feed the load into the shell, the isogrid concept has the floor tied directly into the shell wall at the node points, and the load distribution function is completed by the isogrid shell wall acting as a wide frame. This introduces out-of-plane bending moments, shears, and axial loads in the local shell and longitudinal splices. This is further discussed in the analysis of the floor/fuselage intersection. The out-of-plane shear loading is small and at 90° to the overall distributed shear loading and is therefore, neglected. However, the floor/fuselage intersection study showed that for one "g" cargo loading on the floor, there is:

(1) Axial load across the splice, N_y = 30.1 #/in. (tension)

(2) Moment across the splice, M_y = 64.8 in. lbs./in. (tension outboard)

The check locations chosen were the barrel bay midpoints at Stations 414.5, 511, 631, 775 and 914.5. The total load factor N_z applicable to the floor cargo loading at each check station was obtained from the equation

$$N_z = \frac{(X_{cg} - X)\,\ddot{\theta}}{32.2 \times 12} + N_{z_{C.G.}} \qquad (3)$$

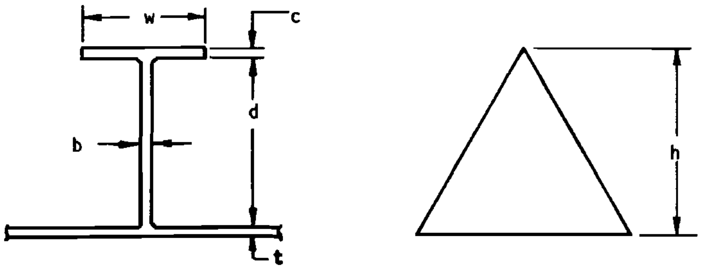
Where $N_{z_{C.G.}}$ is the vertical load factor at the C.G., and $\dot{\theta}$ is the pitch rate.

The instability check conditions (Table VII) were evaluated per the above considerations (see sample calculation, Table X) to identify the splice shown in Table XI. The analysis of the splices followed normal analysis procedures.

Minimum bolt margins of safety are + 0.26 for the hoop splices and + 0.49 for the longitudinal splices.

TABLE VIII ISOGRID SKIN POCKET BUCKLING EQUATIONS

SHELL PROPERTIES

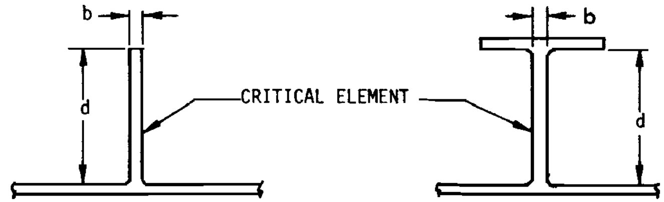


$\alpha = bd/th; \ \mu = wc/th$

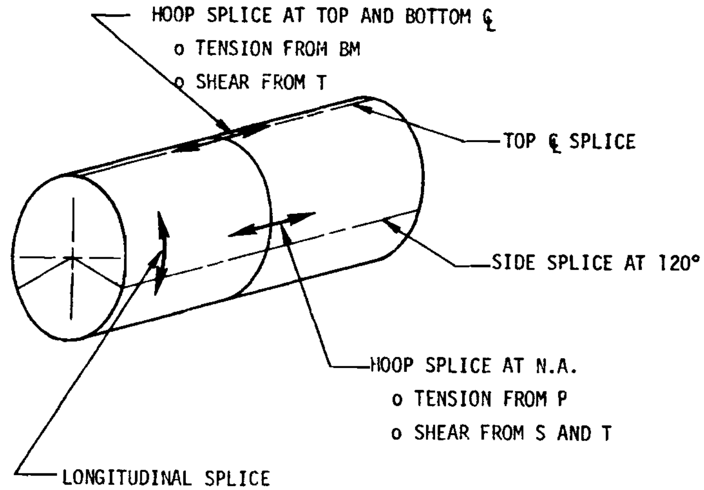
BUCKLING ALLOWANCE	BENDING	$N'_{cr} = 10.2\ Et(1 + \alpha + \mu)\left(\frac{t}{h}\right)^2$
	SHEAR & TORQUE	$V'_{cr} = 23.1\ Et(1 + \alpha + \mu)\left(\frac{t}{h}\right)^2$
LOADS LOAD RATIOS	SIMILAR TO THOSE IN TABLE 6	
INTERACTION (REFERENCE 5)		$R_B + (R_S + R_T)^2 \leq 1.0$

TABLE IX ISOGRID RIB BUCKLING EQUATIONS

RIB PROPERTIES



BUCKLING ALLOWABLE	BENDING	UNCAPPED	$N''_{cr} = 0.616\ Et\ (1 + \alpha)(b/d)^2$
		CAPPED	$N'_{cr} = 3.692\ Et\ (1 + \alpha + \mu)(b/d)^2$
	SHEAR & TORQUE	UNCAPPED	$V'_{cr} = 0.533\ Et\ (1 + \alpha)(b/d)^2$
		CAPPED	$V'_{cr} = 3.199\ Et\ (1 + \alpha + \mu)(b/d)^2$
LOADS & LOAD RATIOS		SIMILAR TO THOSE IN TABLE 6	
INTERACTION (REFERENCE 1)			$R_B + R_T \leq 1.0$



NOTE: KEY FOR LOADS IS:

P - CABIN PRESSURE
BM - DISTRIBUTED BENDING MOMENT
T - DISTRIBUTED TORQUE
S - DISTRIBUTED SHEAR

Figure 16 FUSELAGE SHELL SPLICE LOADING CONDITIONS

TABLE X SAMPLE CALCULATION FOR SPLICE LOADS (STA 847)

ULTIMATE LOADS	MOMENT x 10^{-6}	14,184
	SHEAR x 10^{-6}	54.9
	TORQUE x 10^{-6}	0
	PRESSURE (PSI)	11.25
HOOP SPLICE AT BOTTOM ℄	$(\bar{Y}_{ten})/I$	0.00027
	$(t_{ten})_{eff}$	0.074
	$f_b(t_{ten})_{eff} = MY(t_{ten})_{eff}/I$ (#/in)	283
	PRESSURE LOADS (#/in)	608
	TORQUE SHEAR/TORQUE	14.04 x 10^{-6}
	TORQUE SHEAR (#/in)	0
	Σ AXIAL LOADS (#/in)	891
HOOP SPLICE AT NEUTRAL AXIS	$(Q_{NA})/I$	0.0063
	$V(Q_{NA})/I$ (#/in)	346
	TORQUE SHEAR (#/in)	0
	Σ SHEAR (#/in)	346
	PRESSURE LOADS (#/in)	608
LONGITUDINAL SPLICE AT θ = 120°	$(Q_{120})/I$	0.0058
	$V(Q_{120})/I$ (#/in)	318
	TORQUE SHEAR (#/in)	0
	Σ SHEAR (#/in)	318
	PRESSURE LOADS	1215
LONGITUDINAL SPLICE AT FLOOR LOAD	$(X_{C.G.} - X) = (X_{C.G.} - 914.5)$	-129.57
	PITCHING ACCELERATION $\dot{\theta}$	0
	N_X	-1.50
	$N_Z = 0.00259(X_{CG} - X)\dot{\theta} + N_{Z\ C.G.}$	-1.50
	$N_Y = 30.1\ (N_Z)$(#/in)	-45.1
	$M_Y = 64.8(N_Z)$(in #/in)	-97.2

4.3.2 Cargo Floor/Fuselage Intersection

The inherent bending stiffness of the isogrid fuselage wall is capable of resisting floor loads without adding frames as intermediary members. The analysis procedure includes selection of a critical floor load condition, definition of loads from the floor beam into the fuselage side wall, use of the DAC computer program NATLOCK to define the loads and stresses in the fuselage shell from the floor loads, and finally tailoring of the shell wall to match the loads defined by the NATLOCK program.

The floor loads of Volume I were inspected and the critical condition for the fuselage shell wall determined (300 PSF floor loading over one 48 inch bay length at a 10.1 g load factor). This load, fanned out to 60 inches, results in a 1125 #/in ultimate vertical (down) loading at the floor line intersection into the shell wall. The NATLOCK program gave axial, shear and moment loads both in hoop and longitudinal directions. The hoop loads which are of interest are shown in Table XII.

Candidate panel sections were selected, their properties computed and the least weight section meeting the loading requirements identified. The pertinent equations for hoop stress in the skin and in the circumferential rib (Reference 1) are:

(1) Skin hoop stress,

$$\sigma_y = -M_y \bar{y}_s / I + N_y / t_{eff} \qquad (4)$$

(2) Hoop rib maximum stress

$$\sigma_1 = \frac{E}{K(1-\upsilon^2)} [- \upsilon N_x + N_y] + \frac{E \bar{y}_R}{D(1-\upsilon^2)} [-\upsilon M_x + M_y] \qquad (5)$$

Hoop pressure stresses from the ultimate flight pressure of 12 PSI (differential) were conservatively added to the above tension stresses. This procedure defined the magnitude and location of the shell side wall reinforcement shown in Figure 17.

4.3.3 Transverse Floor Beam Truss Design

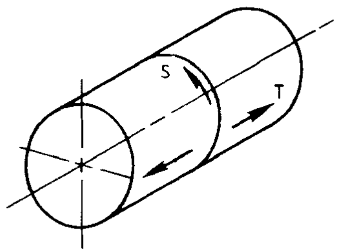
A proposed transverse floor beam truss design used the isogrid shell wall for the lower cap and the floor as the upper cap. Consideration of the curved lower cap of the floor beam is required to define the shell. The curvature causes additional bending moments in the shell (outer cap) which required a difference equation solution. The actual analysis steps included selection of the loads, definition of the model, selection of the section, the difference equation solution, calculation of moments and stresses, and interpretation of the results.

The critical floor load (Volume I) is 300 PSF at 10.1 g's ultimate. This floor load generates an approximately constant 46,000 pound tensile load through the entire lower cap. The actual truss is a twelve bay outer cap which was suitably modelled as a five bay configuration.

The governing equation, after simplification, is

TABLE XI CRITICAL FUSELAGE SHELL SPLICE LOADS

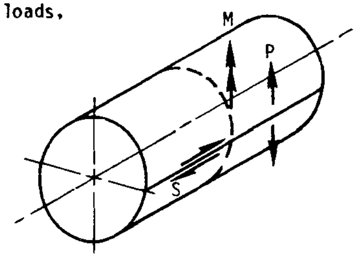
HOOP SPLICE



STATION	TENSION ULTIMATE (#/in)	SHEAR ULTIMATE (#/in)	COMMENT
463	1	1725	MAXIMUM SHEAR LOAD
703	1828	0	MAXIMUM TENSION LOAD

NOTE: * Critical load conditions are determined by the floor loads, see Volume I, Section II.

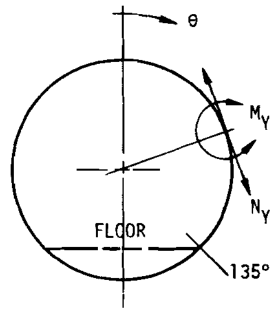
LONGITUDINAL SPLICE



STATION	TENSION (#/in)	SHEAR (#/in)	MOMENT (in #/in)	COMMENTS
463	101.7	1588	219.0	MAXIMUM MOMENT & SHEAR *
847	1170	318	-97.2	MAXIMUM NEGATIVE MOMENT *
847	1260	487	97.2	MAXIMUM COMBINED LOADS *
---	1620	0	0	BURST PRESSURE (P)

TABLE XII FUSELAGE SHELL HOOP LOADS DUE TO FLOOR LOADS

SKETCH



θ (DEGREES)	FORCES N_Y (#/in)	FORCES M_Y (in #/in)
0	+ 7	+98
30	+ 2	-16
60	-12	-175
90	-35	-11
115	+102	+651
125	+505	+666
130	+759	+180
133	+907	-319
137	-340	-925
140	-214	-768
145	-57	-582
155	+68	-187
180	+44	+131

$$w + \frac{d^2 w}{d\theta^2} + \frac{R^2}{EI} M = 0 \qquad (6)$$

where

w is the radial deflection,

θ and R are coordinates, and

M is the bending moment.

In the difference equation solution, the term $\frac{d^2 w}{d\theta^2}$ is written in terms of the deflections on each side of a selected point i, as follows.

$$\frac{d^2 w_i}{d\theta^2} = \frac{1}{12\theta^2} [- w_{i-2} + 16w_{i-1} - 30 w_i + 16w_{i+1} - w_{i+2}] \qquad (7)$$

A set of simultaneous equations result which, when solved, give values of the deflections w_i. Then, the moment at any station is obtained from

$$M_i = - \frac{EI_i}{R^2} [w_i + \frac{d^2 w_i}{d\theta^2}] \qquad (8)$$

where the second differential is again expressed in terms of the deflections.

The selected section is shown in Figure 18. The adjacent hoop ribs were considered to act with the center rib through the diagonal interconnecting ribs. The resulting approximate stresses, including pressure, are also shown in Figure 18.

4.3.4 Miscellaneous Analyses

Brief analyses were also made of the following areas:

- Out-of-round fuselage, Station 366 to approximately 511
- High shear region under the wing
- Aft fuselage, Station 782 to 1437

These analyses showed that the isogrid wall could beam the pressure loads to the frames installed in the out-of-round fuselage; that the isogrid shell under the wing could support the wing drag loads; and that the aft fuselage isogrid shell general stability is adequate for the baseline applied distributed loads.

4.4 ACOUSTICS

The fuselage of an aircraft is exposed to external acoustic loads originating from the air flow over the vehicle (boundary layer noise) and engine noise. The characteristics of isogrid construction under these acoustic loads are of

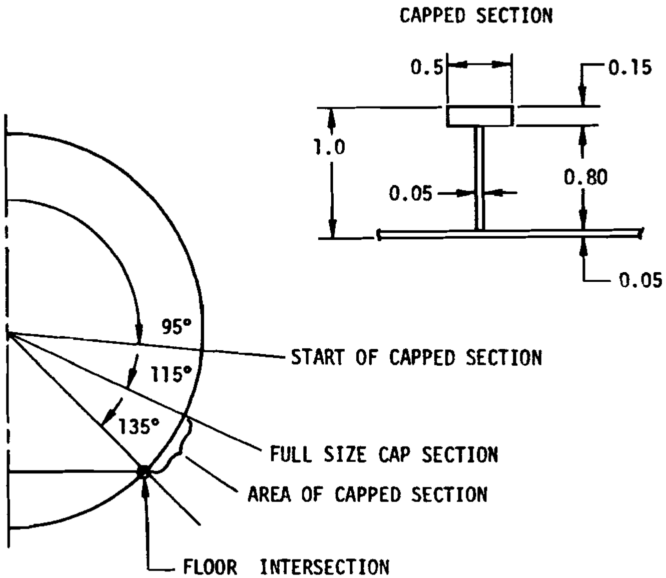
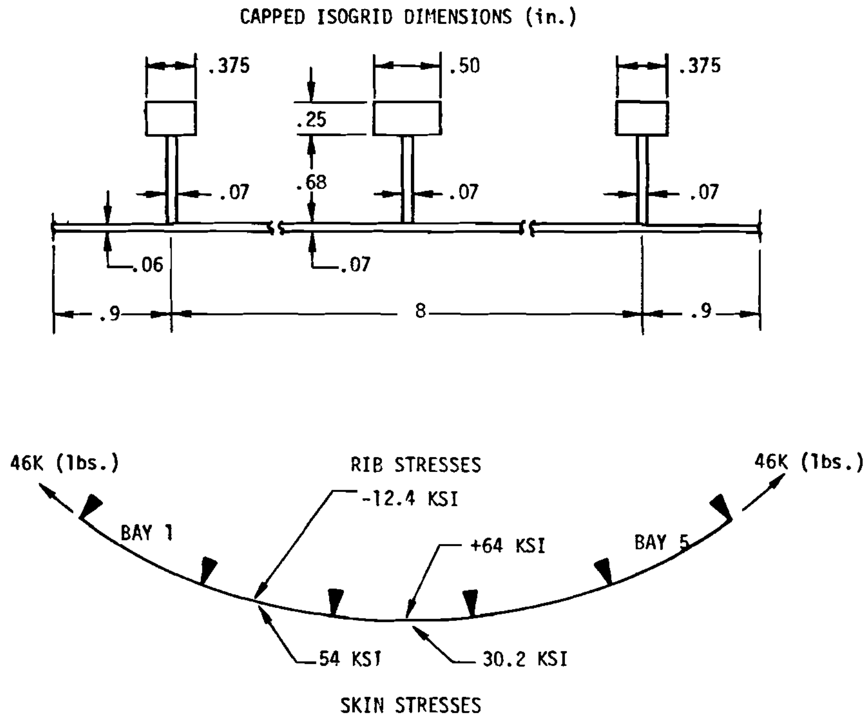


Figure 17 FUSELAGE ISOGRID SIDEWALL DESIGN TO RESIST FLOOR LOADS



NOTE: RESULTING STRESSES FOR 5 BAY MODEL

Figure 18 FUSELAGE SHELL CAPPED ISOGRID DIMENSIONS AND STRESSES interest for two reasons. These are the possible fatigue of the panels and the acoustic energy that will be radiated into the aircraft cabin. The acoustic fatigue problem is discussed in Section 4.1.4. The effect of isogrid construction on internal acoustic levels are discussed below.

4.4.1 Internal Acoustic Levels

The aircraft cabin internal acoustic levels are highly dependent on the internal acoustic treatment. For the purpose of this study, it is assumed that the internal treatment will be equally as effective, easy to apply, economical and compact for isogrid as for the standard construction. This limits the discussion to the relative effectiveness of the structural types in transmitting noise.

A method of evaluating the relative merits of two panels is to compare their transmission loss (TL). Transmission loss data is available for a 4 ft x 6 ft DC-10 structural panel and a curved 20" x 42" isogrid panel. Neither panel is identical structurally to that included in this study, but the tests do give insight into the relative behavior of the two structural configurations.

Both tests were performed in a McDonnell Douglas facility by placing the panels in a window between available reverberant and anechoic chambers (Figure 19). Acoustic energy was introduced into the reverberation chamber and acoustic measurements were made on each side of the panel being tested.

The DC-10 panel was of conventional aircraft construction and had a 0.071 inch thick aluminum skin. Four measurements were made on the reverberation chamber side of the panel and 7 on the anechoic chamber side six inches from the panel surface. The acoustic levels measured on each side of the panel were averaged. The differences, in dB, represent a measure of the transmission loss and are plotted in Figure 20.

In addition, the standard mass law transmission losses have been added to the figure to aid in comparison. The reduction in transmission loss above 4,000 Hz results from coincidence transmission (f_c = coincidence frequency).

The aluminum isogrid panel tested was curved and had a basic skin thickness of 0.051 inches. Because of the size and the mounting method dictated by the curvature, the measurement method differed somewhat from that used on the DC-10 panel.

Measurements on the anechoic side were made with three microphones 2 inches from the panel. In the reverberation room, one measurement was made two inches from the center of the panel and two additional measurements were made out in the room. The TL was obtained by subtracting (in dB) the average of the anechoic room measurements from the average of the two measurements made out in the reverberation room above 1000 Hz. Below 1000 Hz, the measurement made at the panel less 3 dB (to account for reflections) was used to define the field in the reverberation chamber. The resulting TL is shown in Figure 21 along with the mass law transmission loss.

Mass law transmission loss is a function of frequency and the surface density. The effectiveness of the two panel types can be compared by comparing the deviation of each from mass law. This comparison can be made directly by reducing

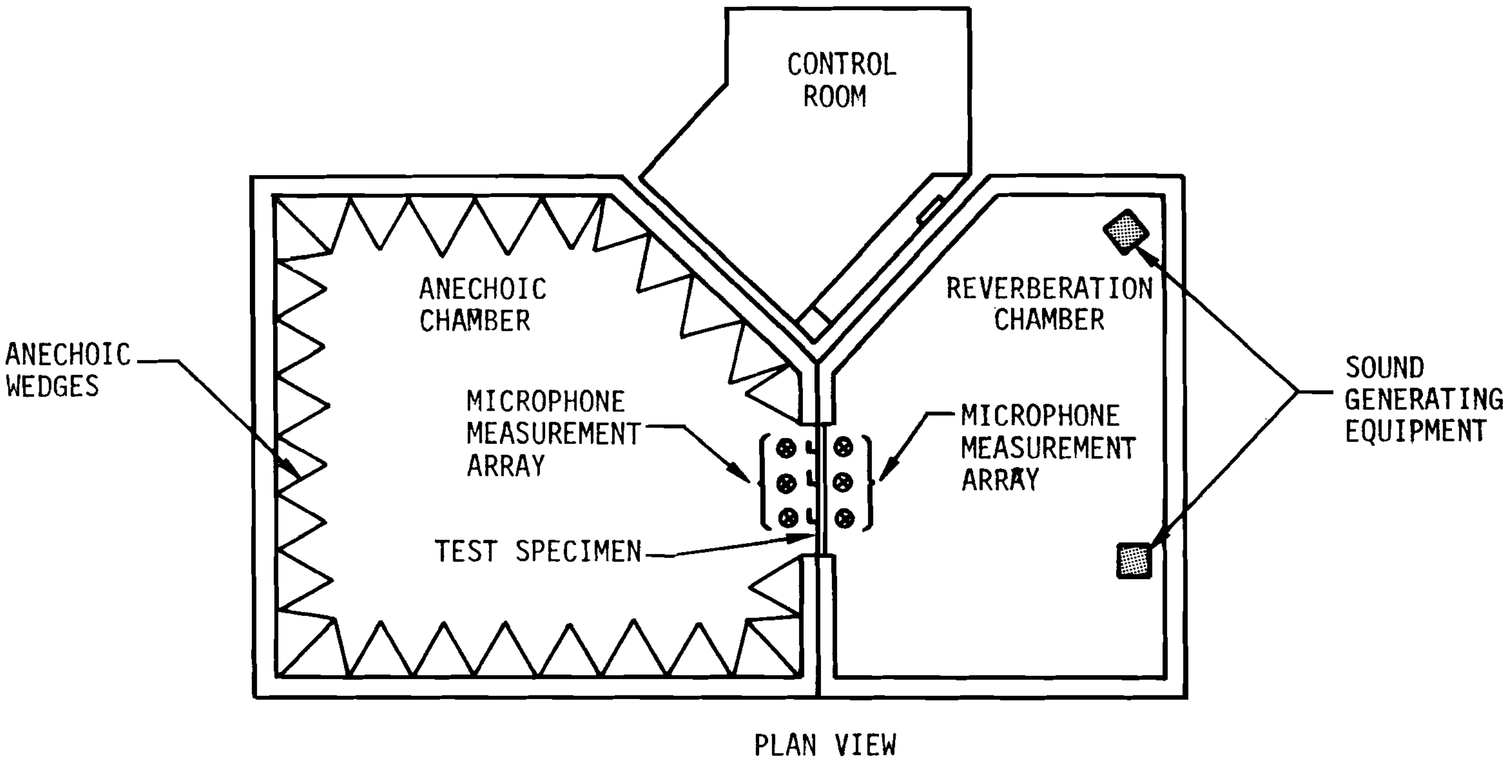


Figure 19 REVERBERANT/ANECHOIC CHAMBER TEST FACILITY

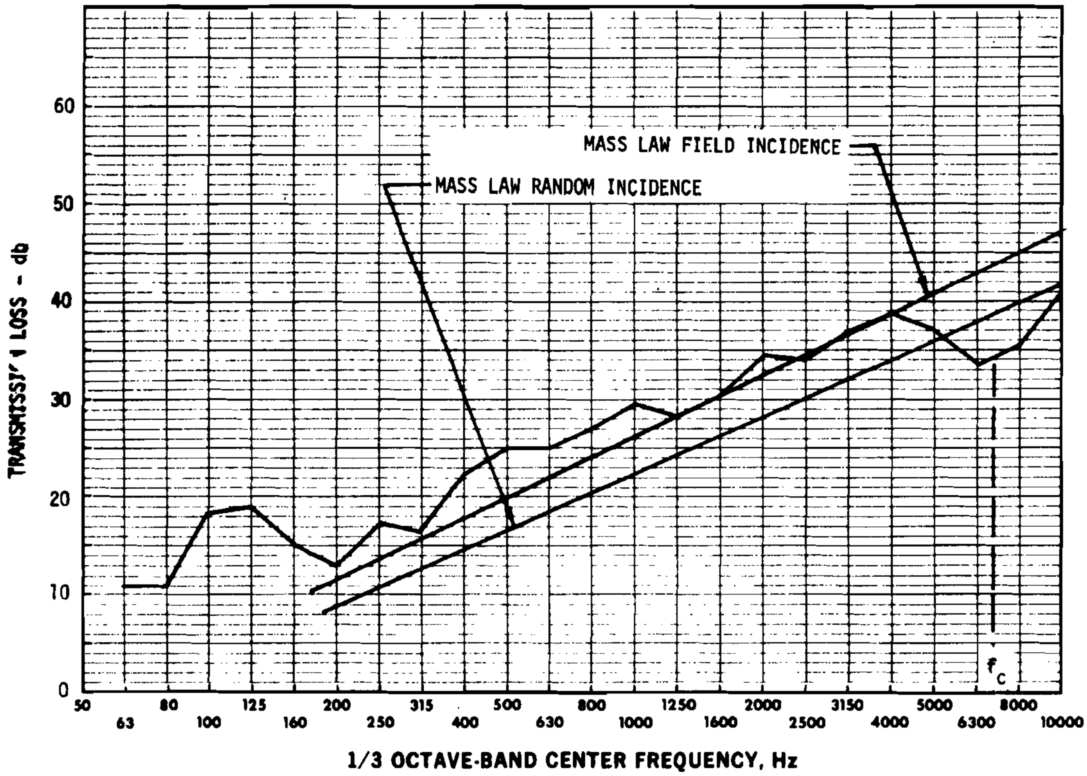


Figure 20 TRANSMISSION LOSS FOR TYPICAL AIRCRAFT PANEL (SKIN GAGE OF .071 IN.)

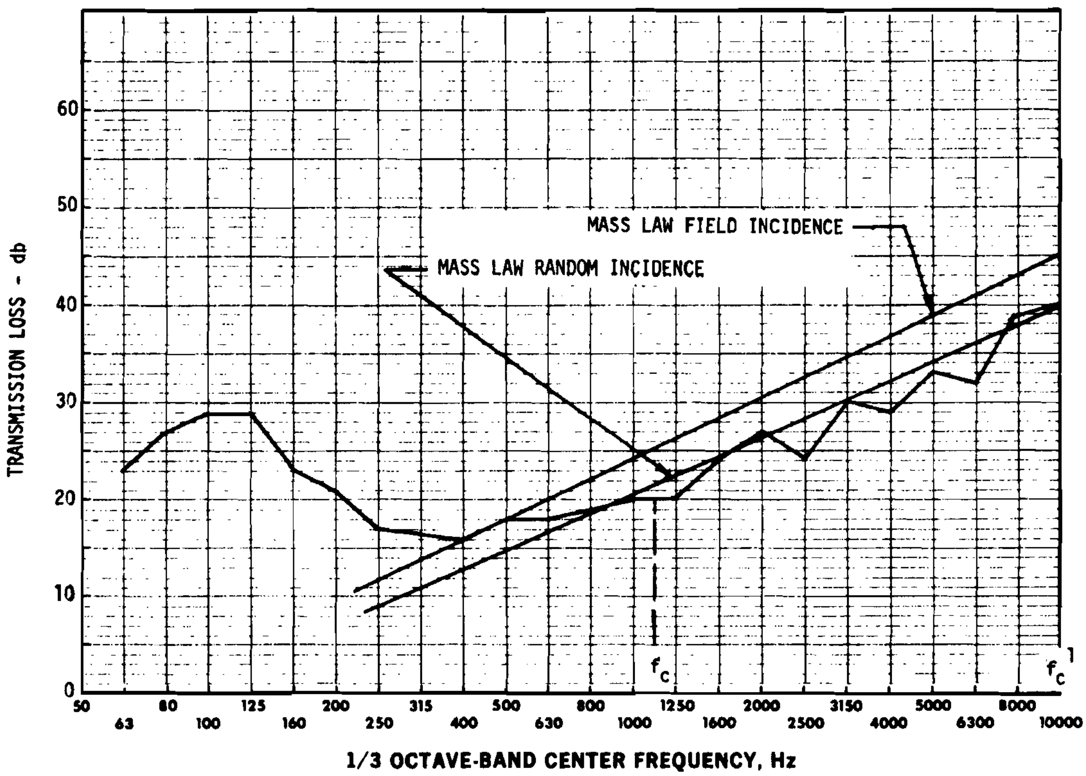


Figure 21 TRANSMISSION LOSS FOR ISOGRID PANEL (SKIN GAGE OF .051 IN.)

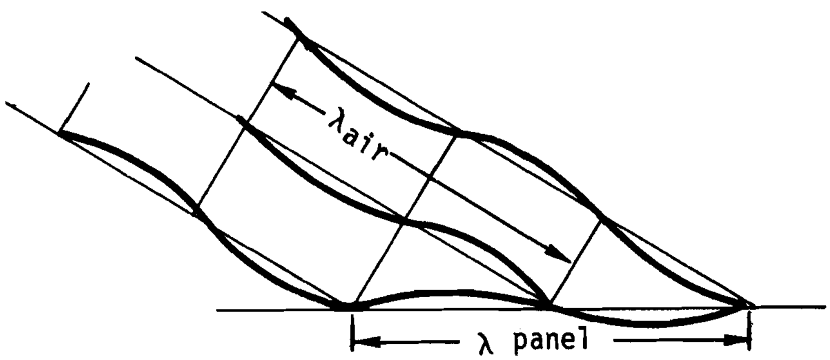
the transmission loss for the typical skin until its mass law is the same as that for the isogrid. This gives a direct comparison as shown in Figure 22.

The transmission loss is higher in the low frequencies for the isogrid than for the standard panel. This results from the stiffness of the isogrid, the curvature of the panel and the smaller size of the panel. The data is not sufficient to determine if the lower transmission loss would exist for a total fuselage structure.

The transmission loss is lower for the isogrid than for the standard panel in the high frequencies. The reasons for this are not as obvious.

It is assumed that the inherently low damping of the isogrid would lower the TL. However, the mounting method used did introduce some damping into the structure. In addition, the coincidence effects will be much different for isogrid structure.

Coincidence occurs where the trace velocity along a panel of an impinging acoustic wave equals the propagation velocity of a bending wave in the panel. This results in matching the wave lengths as shown below.



The indicated matching maximized the response (joint acceptance) and results in a nearly transparent panel. However, since the velocity is a function of frequency, this effect will occur at only one frequency for a given angle of incidence. Likewise, it will occur at only one angle for a given frequency. The net effect is that a panel has selective transmission as a function of frequency and angle above the coincidence frequency. The coincidence frequency is the lowest frequency where coincidence can occur. This is at grazing incidence and occurs where the bending wave velocity equals the speed of sound in air.

The propagation velocity for a bending wave in a plate is: (Reference 5)

$$u = \left(\frac{4\pi^2 EI}{\rho}\right)^{1/4} f^{1/2} \tag{9}$$

where

EI = bending stiffness

ρ = surface density

f = frequency

and

$$f_c = u_a^2 \left(\frac{\rho}{4\pi^2 \, EI}\right)^{1/2} \qquad (10)$$

where

f_c = coincidence frequency

u_a = speed of sound in air

One of the structural advantages of isogrid is the high value of $\frac{EI}{\rho}$. If $\frac{EI}{\rho}$ increases, f_c must decrease. The coincidence frequency for the isogrid structure tested was calculated to be 1,200 Hz instead of 10,000 Hz for a 0.05 panel.

The low transmission loss of the isogrid structure in the higher frequency is primarily due to coincidence transmission. In addition to the obvious implications, this would also dictate a much more detailed description of the acoustic field than is normally required because of the highly directional characteristics of the coincidence effect.

For boundary layer excitation, coincidence occurs when the convection velocity in the boundary layer equals the bending velocity in the structure. This velocity is sixty percent of the free stream velocity for high frequencies and for subsonic flight (Reference 6). This reduces the coincidence frequency to 2500 Hz for the standard construction considered here and 400 Hz for the isogrid.

The calculated response for standard structure is much lower in the high frequencies for boundary layer excitation than for a reverberant field of the same level of excitation as shown in Figure 23 (calculated based on Reference 6). The large decrease in the high frequency is attributed to a reduction of response above the coincident frequency. If this is the case, then the area of low response will be shifted down to around 400 Hz for the isogrid structure and will result in low internal acoustic levels above 500 Hz due to boundary layer excitation. This conclusion must be confirmed by analysis and test.

4.4.2 Conclusion

Based on the limited data available, it appears that isogrid construction would be comparable to standard construction in the low and mid-frequency ranges. At the high frequencies (> 800 Hz), the low coincidence frequency results in a low random incidence transmission loss. However, the effect of this is highly dependent on the type of acoustic field encountered. It is assumed that isogrid would be equivalent to standard construction except for

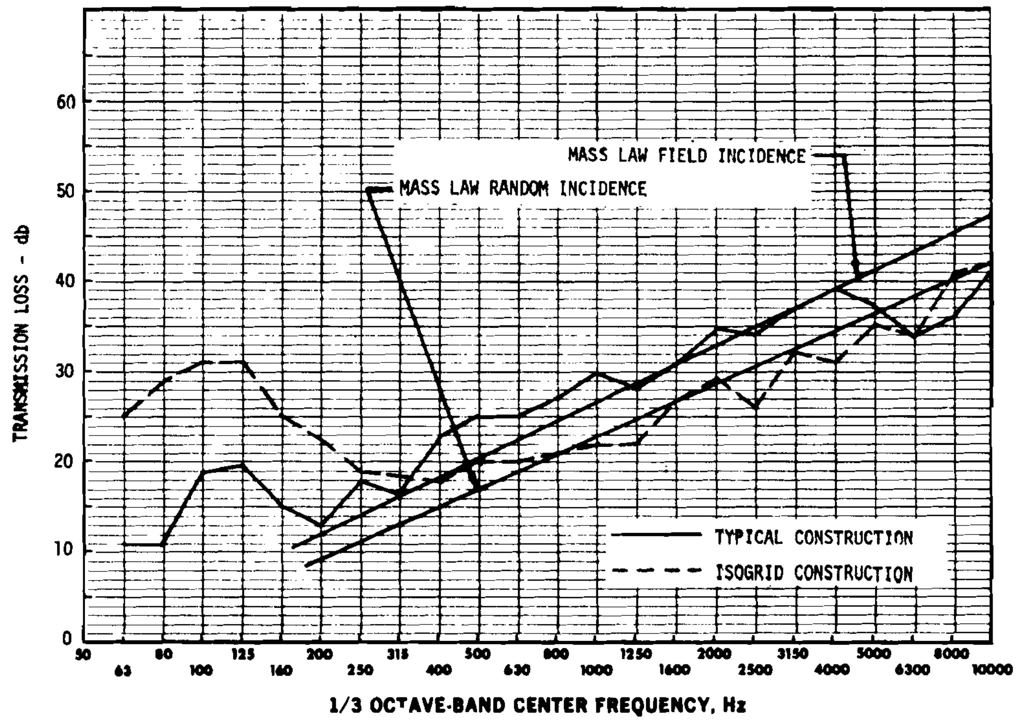


Figure 22 COMPARISON OF TRANSMISSION LOSS

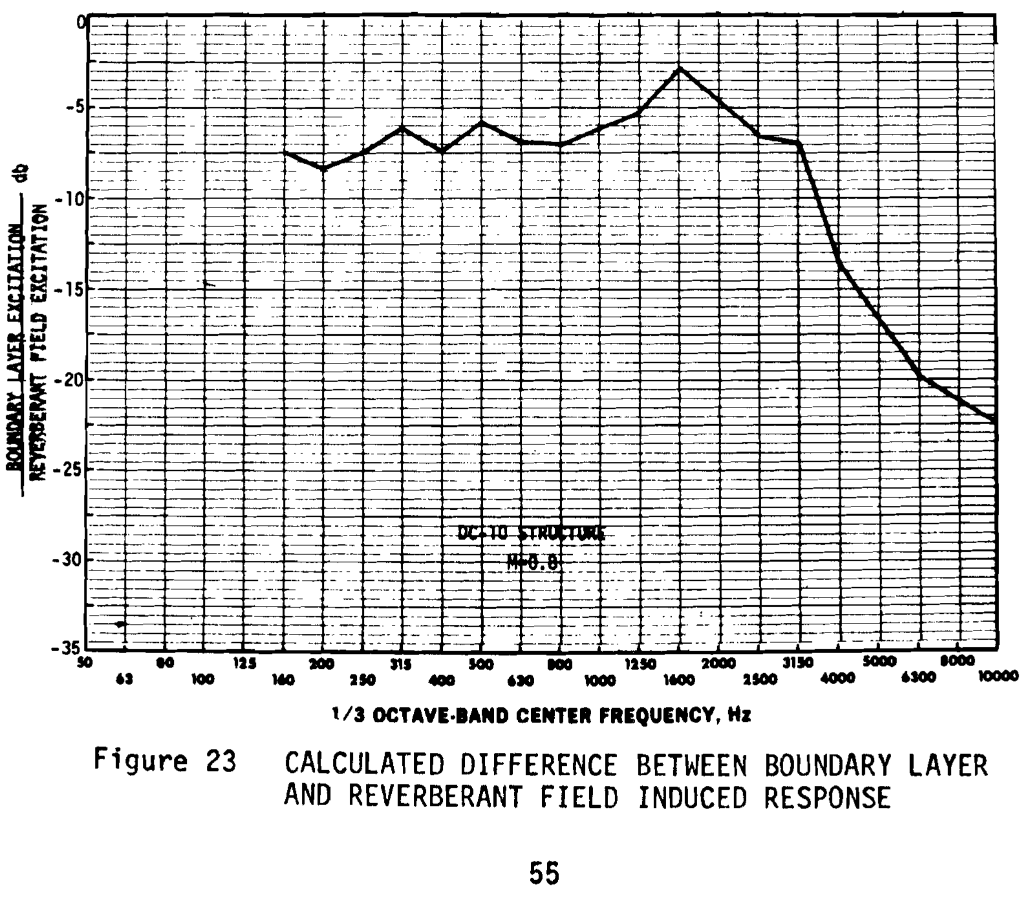


Figure 23 CALCULATED DIFFERENCE BETWEEN BOUNDARY LAYER AND REVERBERANT FIELD INDUCED RESPONSE

the transmission at coincidence. Transmission at coincidence is dependent on the frequency and angle of incidence of the exciting field and may occur during the takeoff and landing portions of flight. During cruise, when the boundary layer is the primary source, isogrid may be superior to standard construction.

In general, it appears that isogrid would alter the problems encountered in predicting and controlling the internal acoustic levels. Ground and flight tests combined with a detailed analytical effort would be required to define the interior noise for a fuselage with isogrid structure and to reduce the noise to a point where acceptable levels are achieved.

4.5 THERMAL INSULATION

This section discusses the impact of isogrid fuselage construction on the C-15 cargo compartment thermal insulation requirements.

It was found that there was no need to change the thickness of insulation from that selected for conventional skin and stringer fuselage construction. Cargo compartment temperatures are not significantly affected but are very slightly better. The major impact is an insulation weight saving of 300 lbs. This saving is possible because a large number of fuselage frames have been eliminated. A considerably shorter developed length of insulation is therefore involved, since the insulation batts follow the interior contour for adequate attachment and insulation support.

Insulation thickness in some aircraft is determined by acoustic rather than thermal considerations; however, this section is devoted only to thermal considerations. The same air conditioning system selected for the C-15 is retained for the isogrid study, and the same interior temperatures are required. Original calculations and data used in the analysis are found in Reference 1 of Volume I.

4.5.1 Insulation System Description

The C-15 thermal insulation system comprises a four-inch thick batt of 0.6 lb/ft^3 fiberglass installed as shown in Figure 24. The insulation is compressed to one inch thickness wherever it passes over a frame, and follows frame and skin contours for attachment and support. Compression of the insulation has an adverse effect on insulating capability, but compression occurs only over a small percentage of the total fuselage.

The insulation installation for isogrid fuselage construction is also shown in Figure 24 at a typical frame station. However, with the isogrid construction, there are only about 50% as many frames involved in the fuselage. There is thus a slight improvement in insulating capability and a rather significant reduction in length of insulation batt, and thus in insulation weight.

The cargo compartment thermal conductance for the C-15 with conventional skin and stringer construction has been calculated to be 634 BTU/hr-°F. The corresponding figure for isogrid construction is 618 BTU/hr-°F, i.e., 3% less.

4.5.2 Air Conditioning Performance

The C-15 is air conditioned with two C-141 refrigeration units. One-third of the total flow is delivered to the flight deck and two-thirds to the cargo compartment. The flight deck thermal conductance is estimated to be 100 BTU/hr-°F. Cargo compartment thermal conductances for conventional and isogrid constructions have been cited in the previous section. Other information needed to make performance predictions is given in Figure 25. Air conditioning system performance calculated on the above basis is presented in Table XIII for both types of fuselage construction.

It is evident from Table XIII that the thermal performance is not significantly affected by changing to the isogrid construction, but is very slightly better.

4.6 WEIGHT ANALYSIS

The fuselage shell aft of Station 366 was replaced by an isogrid shell which provided a significant reduction in frame weight in the cylindrical section of the fuselage, but provided a net increase of 436 lb. relative to the baseline fuselage shell. (Refer to Table XIV.) The unresized fuselage weight increase was held to 298 lb. due to the reduction in cargo floor weight by the use of boron infiltrated aluminum extrusions.

Weight savings realized by selecting Wing Concept Number 1 for the wing (Volume I, Figure 67), honeycomb cover panels for the horizontal stabilizer (Volume I, Figure 86), and honeycomb cover panels and reinforced spar caps for the vertical stabilizer (Volume I, Figure 88), offset the 298 lb. net weight increase of the fuselage. This allows the aircraft to be resized downward as shown in Table XV and Table XVI.

The growth factors in Table XVII compare closely with the similar values shown in Volume I, Table XX.

A material description for the completely resized isogrid configuration is shown in Table XVIII.

The cost weights and AMPR weights for the baseline, unresized, partially resized (fixed engine size) and the completely resized aircraft are tabulated in Table XIX.

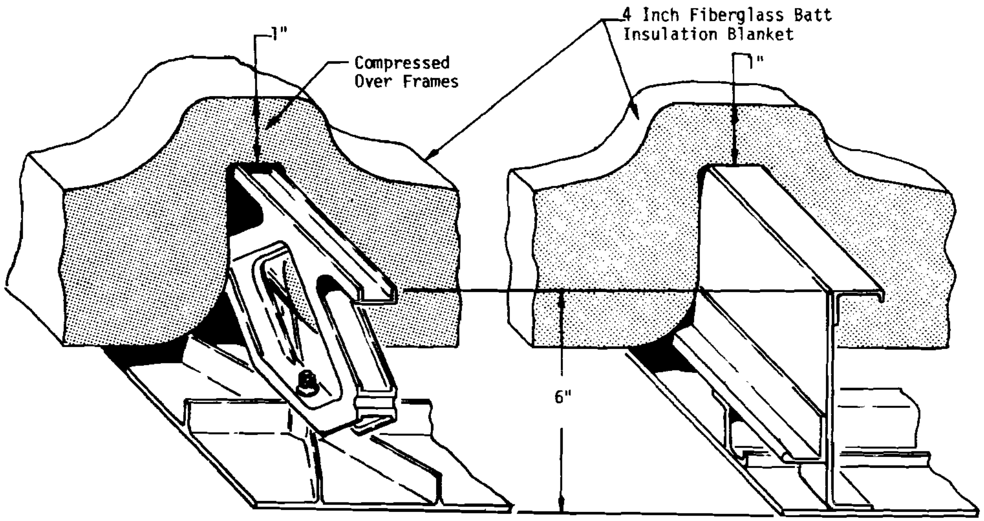


Figure 24   FUSELAGE SHELL COMPARIOSN FOR INSULATION STUDY

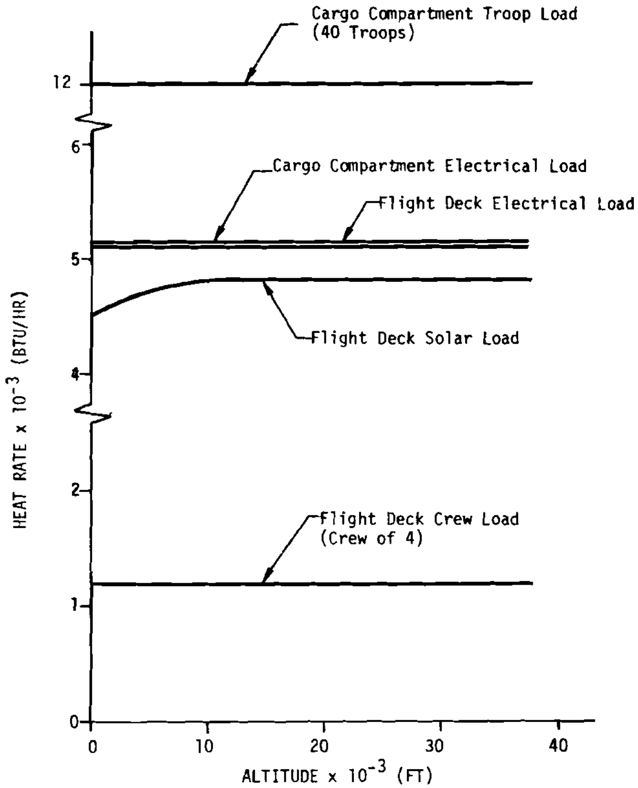


Figure 25   BASELINE AIRCRAFT FUSELAGE HEAT LOADS

TABLE XIII AIR CONDITIONING SYSTEM PERFORMANCE

Case		STOL	CTOL	CTOL	CTOL	GROUND OPER.
Condition		TAKEOFF	CRUISE	DESCENT	HOLD	ON APU**
MIL STD 210 Atmosphere		Hot*	Hot*	Hot*	Hot*	Hot*
Altitude	Ft.	0	35,000	25,000	15,000	0
Mack No.		0.115	0.070	0.602	0.24	0
<u>Ambient Conditions</u>						
Pressure	Psia	14.7	3.47	5.46	8.30	14.7
Temperature	°F	103.0	-30.10	6.70	44.90	103.0
<u>Compartment Temperature</u>						
Conventional Construction	°F	83.0	72.00	72.00	72.00	76.5
Isogrid Construction	°F	82.5	72.00	72.00	72.00	76.0

*For corresponding COLD day conditions engine bleed air is hot enough to maintain flight deck and cargo compartment at 80°F.

**Model GTCP85-180D APU (Generator electrical load of 40 kw).

TABLE XIV ADVANCED CONCEPT STRUCTURAL WEIGHTS							
	BASELINE	UNRESIZED	% SAVED	COMPLETELY RESIZED	% SAVED	PARTIALLY RESIZED	% SAVED
Wing (Concept #1)	(18,765)	(17,763)	5.3	(17,473)	6.9	(17,307)	7.8
Box Structure	9,118	8,116	11.0	7,977	12.5	7,908	13.3
Remainder	9,647	9,647	0	9,496	1.6	9,399	2.6
Horizontal Tail	(3,234)	(3,031)	6.3	(3,003)	7.1	(2,983)	7.8
Box Structure	1,749	1,546	11.6	1,532	12.4	1,522	13.0
Remainder	1,485	1,485	0	1,471	0.9	1,461	1.6
Vertical Tail	(3,460)	(3,288)	5.0	(3,256)	5.9	(3,262)	5.7
Box Structure	1,475	1,303	11.7	1,290	12.5	1,293	12.3
Remainder	1,985	1,985	0	1,966	1.0	1,969	0.8
Fuselage *	(24,367)	24,665	-1.2	(24,609)	-1.0	(24,612)	-1.0
Shell (366-1437)	7,625	8,090	-6.1	8,090	-6.1	8,090	-6.1
Floor (366-982)	1,841	1,702	7.6	1,702	7.6	1,702	7.6
Remainder	14,901	14,873	0	14,817	0	14,820	0

*Isogrid Shell

TABLE XV ISOGRID FUSELAGE AIRCRAFT DESCRIPTION				
VEHICLE DESCRIPTION	BASELINE	UNRESIZED	COMPLETELY RESIZED	PARTIALLY RESIZED
Takeoff Weight - STOL (Lb)	150,000	150,000	147,872	147,992
Wing Area (Ft^2)	1,740	1,740	1,715	1,699
Engine Description	JT8D-17	JT8D-17	JT8D-17 Type	JT8D-17
Engine Thrust (Lb/Eng)	14,900	14,900	14,687	14,900
Horizontal Tail Area (Ft^2)	643	643	637	627
Vertical Tail Area (Ft^2)	462	462	458	458
Horizontal Tail Length (In.)	743	743	743	743
Vertical Tail Length (In.)	616	616	616	616
Horizontal Tail Volume	1.323	1.323	1.340	1.350
Vertical Tail Volume	0.1235	0.1235	0.1250	0.1270
Wing Loading (PSF)	86.2	86.2	86.2	87.1
Thrust Ratio	0.3973	0.3973	0.3973	0.4027
Fuel Fraction	0.1318	0.1390	0.1325	0.1325
Fuselage Diameter (In.)	216	216	216	216
Fuselage Length (In.)	1,318	1,318	1,318	1,318

TABLE XVI GROUP WEIGHT STATEMENT FOR ADVANCED STRUCTURE

	BASELINE	UNRESIZED	% SAVED	COMPLETELY RESIZED	% SAVED	PARTIALLY RESIZED	% SAVED
Wing	18,765	17,763	5.3	17,473	6.9	17,307	7.8
Horizontal Tail	3,234	3,031	6.3	3,003	7.1	2,983	7.8
Vertical Tail	3,460	3,288	5.0	3,256	5.9	3,262	5.7
Fuselage (Isogrid)	24,367	24,665	-1.2	24,609	-1.0	24,612	-1.0
Landing Gear	7,741	7,741	0	7,631	1.4	7,637	1.3
Flight Controls	3,966	3,966	0	3,931	0.9	3,912	1.4
Propulsion	21,709	21,709	0	21,399	1.4	21,709	0
Fuel System	768	768	0	763	0.7	759	1.0
APU	966	966	0	966	0	966	0
Instruments	1,453	1,453	0	1,453	0	1,453	0
Hydraulics	1,436	1,436	0	1,424	0.8	1,424	0.8
Pneumatics	340	340	0	340	0	340	0
Electrical	1,736	1,736	0	1,736	0	1,736	0
Avionics	2,045	2,045	0	2,045	0	2,045	0
Furnishings	5,497	5,497	0	5,497	0	5,497	0
Air Conditioning	837	837	0	837	0	837	0
Ice Protection	254	254	0	254	0	254	0
Handling Gear	150	150	0	150	0	150	0
Structural Weight (No. L.G.)*	53,922	52,843	2.0	52,379	2.9	52,260	3.2
Structural Weight (With L.G.)*	61,663	60,584	1.7	60,010	2.7	59,897	2.9
Manufacturer's Empty Weight	98,724	97,645	1.1	96,767	2.0	96,883	1.9
Operator's Items	4,510	4,510	---	4,507	---	4,505	---
Operator's Empty Weight	103,234	102,155	1.0	101,274	1.9	101,388	1.8
Payload	27,000	27,000	---	27,000	---	27,000	---
Return Segment Fuel	19,766	20,845**	---	19,598	---	19,604	---
Takeoff Weight - STOL	150,000	150,000	---	147,872	1.4	147,992	1.3

*Includes Nacelle & Pylon Structure (4,096 Lb. for Baseline); ** Extended Mission

TABLE XVII GROWTH FACTORS FOR ADVANCED AIRFRAME

ITEM	INITIAL WEIGHT REDUCTION	COMPLETELY RESIZED		PARTIALLY RESIZED	
		ΔOEW	ΔTOGW	ΔOEW	ΔTOGW
Wing	1,002	1,292	1,292	1,458	1,458
Horizontal Tail	203	231	231	251	251
Vertical Tail	172	204	204	198	198
Fuselage (Isogrid)	- 298	- 242	- 242	- 245	- 245
Miscellaneous	--	475	475	184	184
Fuel	--	--	168	--	162
Total Weight Reduction (Lb)	1,079	1,960	2,128	1,846	2,008
Growth Factor	--	1.82	1.97	1.71	1.86

TABLE XVIII RESIZED STRUCTURE MATERIAL WEIGHT BREAKDOWN (#1 WING - ISOGRID FUSELAGE)

COMPONENT	GLASS, FIBER-GLASS	FILLER, ATTACH, PAINT	ADHE-SIVES	ALUMI-NUM FORGING	ALUMINUM NOT FORGING	STEEL	TITANIUM	ALUMINUM HONEY-COMB	HIGH DENSITY METAL	BORON* / BORON ALUMINUM	TOTAL
Wing Structure											(17,473)
Box		177			7,800						7,977
Remainder	774	93		3,147	1,783	670	2,884		145		9,496
Horizontal Tail Structure											(3,003)
Box		113	110		1,195			114			1,532
Remainder		44		304	1,123						1,471
Vertical Tail Structure											(3,256)
Box		15	59	111	917			133		55*	1,290
Remainder		52		380	1,441	93					1,966
Fuselage Structure											(24,609)
Shell (Forward of 366)		20			251						271
Shell (366 to 982)		156			5,242						5,398
Shell (Aft of 982)		66			2,626						2,692
Other Primary Structure	681	78		2,220	1,517						4,496
Cargo Floor, Ramp & Supports	402	180		320	2,990	200				1,702	5,794
Remainder	232	263		247	4,889	327					5,958
TOTAL	2,089	1,257	169	6,729	31,774	1,290	2,884	247	145	55* / 1,702	48,341

TABLE XIX ADVANCED CONCEPT AIRFRAME (ISOGRID FUSELAGE) COST WEIGHT AND AMPR WEIGHT

ITEMS		BASELINE	ADVANCED CONCEPT		
			UNRESIZED	COMPLETELY RESIZED	PARTIALLY RESIZED
MANUFACTURER'S EMPTY WEIGHT		98,724	97,645	96,767	96,883
LESS	ROLLING ASSEMBLY	-3,349	-3,349	-3,301	-3,304
	ENGINES	-13,320	-13,320	-13,130	-13,320
COST WEIGHT Σ		82,055	80,976	80,336	80,259
LESS	STARTERS	-105	-105	-104	-105
	APU	-410	-410	-410	-410
	INSTRUMENTS	-578	-578	-578	-578
	BATTERY & A.C. SUPPLY	-450	-450	-450	-450
	AVIONICS (BLACK BOXES)	-1,183	-1,183	-1,183	-1,183
	AIR CONDITIONING UNITS	-242	-242	-242	-242
	HYDRAULICS (DROP OUT GENERATOR)	-71	-71	-71	-71
AMPR WEIGHT Σ		79,016	77,937	77,298	77,220

SECTION V

MANUFACTURING METHODS

5.1 METAL PROCESSES

Integrally machined isogrid stiffened panels are proposed for the constant diameter section of the fuselage and the aft section where compound curvature is necessary on exterior mold lines. Conventional manufacturing processes will be used in the fabrication of these panels.

5.2 METAL REMOVAL

The isogrid stiffened panels will be machined from aluminum alloy plate stock which involves the removal of a large volume of material. Precision machining is required to insure dimensional conformance and to meet surface finish requirements. The design of the isogrid panels is coordinated with manufacturing to obtain maximum efficiency when machining. Designing pockets with radii that permit correct tool loading, the use of repetitious grid patterns, and establishing geometry of the patterns to meet machining and forming requirements simplify manufacturing of the panels.

5.2.1 Machining

Multi-spindle numerically controlled machines are the primary machining techniques to be used to fabricate the isogrid panels. Direct computer controlled machines will be used to provide more rapid program verification capability and response to engineering design changes. The numerically controlled machines should use at least four spindles operating simultaneously for maximum efficiency when machining repetitious grid patterns. Cutters using replaceable lockable carbide inserts will be used to provide the required surface finish and insure lower tool replacement costs. The cutters will have the capability to end cut, side cut, and undercut to machine both flanged and unflanged stiffeners.

5.3 FORMING

The forming of integrally stiffened panels, including isogrid, has been performed on brake presses and creep apparatus. The brake forming process is limited to producing simple contours only, and creep forming is expensive and constrained by part size. Forming by the process of shot peening is a promising candidate for isogrid panels.

The process of forming by shot peening is widely used among manufacturing industries and many advances have been made through research and development. Shot peening techniques were used to form many integrally stiffened panels for commercial and military aircraft.

Advances made by MDC over the past year in the shot peen forming of isogrid panels to simple and compound contours support shot peening techniques as being both economical and reliable. Shot peening tests were conducted on isogrid panels having an overall thickness of 1/2 inch with an 0.063 skin gage. The isogrid panels were formed to a 118 inch axial radius and to a 90 inch spherical radius, respectively.

On the aft section isogrid panels, where compound curvature is required, the isogrid will be designed similar to sheet metal layouts for conical shapes. Isogrid axes will not be parallel in the flat plane, but will be oriented into parallel rows after forming. The exact geometry of the patterns will be determined empirically by coordinating machined patterns with shot-peen forming of the panels into final contour.

5.4 MANUFACTURING METHODS DEVELOPMENTS REQUIRED

Further development of the process of shot peen forming of isogrid panels is the principal requirement for manufacture. Depending on the size of the panels, larger facilities may be required for heat treatment and chemical milling processes.

In support of the concept of shot peen forming of isogrid fuselage skin panels, MDC has a development program in progress to evaluate and demonstrate the shot peen forming capability for contouring isogrid panels with stiffeners raised approximately one inch in height. Consideration must also be given to node areas and the degree and effect of stress distribution between peened and unpeened areas.

SECTION VI

NONDESTRUCTIVE INSPECTION

6.1 NDI INSPECTION SENSITIVITY

The discussion for NDI inspection of materials, as found in Section 9.1 of Volume I, is applicable to the isogrid fuselage shell structure.

6.2 FABRICATION INSPECTION

The wing box and empennage box structure NDI fabrication inspection discussion (Section 9.1.2, Volume I) is applicable for the airframe concept containing the isogrid fuselage shell.

6.2.1 Isogrid Fuselage Shell

The fuselage shell from Station 372 aft to Station 1437 is an integral isogrid concept. The material selected is the 7475-T76 aluminum plate. The longitudinal and circumferential splice designs are shown in Figure 5. The skins would require an ultrasonic inspection before machining the isogrid pattern. The skins are machined and then are formed to contour by shot-peening. Penetrant inspection is then required on the completed panels. Penetrant or eddy-current inspection must be done at the critical splice joint attach holes. An ultrasonic or eddy-current inspection device should be built into the isogrid machining tool to measure the thickness of the skin (t) and web (b) (see Figure 26). If the thickness measuring devices cannot be incorporated, then a separate inspection station is required to check the dimensions.

6.3 IN-SERVICE INSPECTION

The discussion on Special Visual Inspectable and Depot or Base Level Inspectable structures in Section 9.2, of Volume I, is applicable for the isogrid fuselage shell.

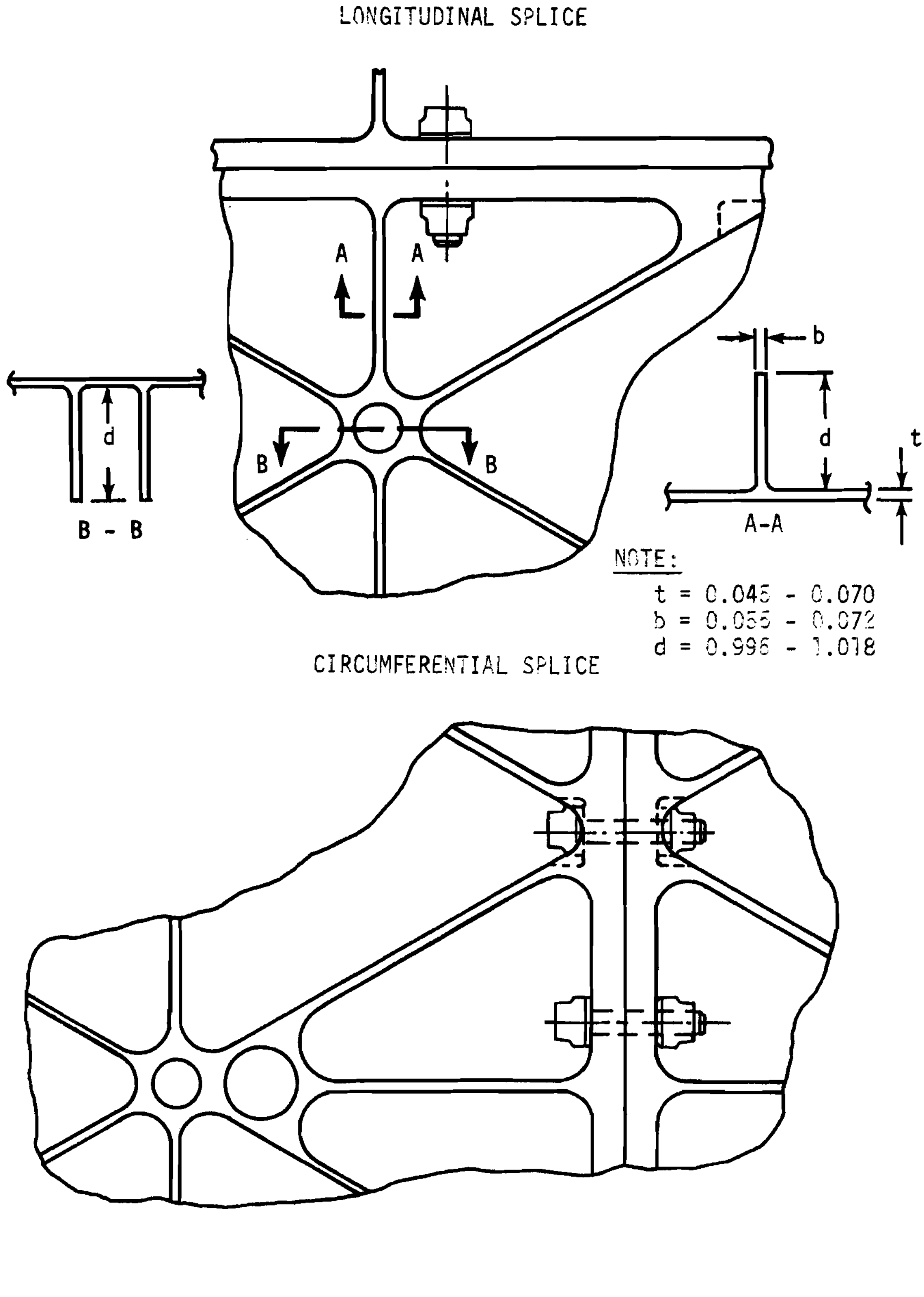


Figure 26 FUSELAGE ISOGRID SPLICES

SECTION VII

COSTS

Volume I of this report contains the detailed acquisition and life cycle cost analysis results of the baseline and of a new concept aircraft which incorporates selected new design concepts and materials in the structure of the wing and empennage boxes and the fuselage shell. The new concept aircraft in this case had a honeycomb sandwich fuselage shell.

A second new concept aircraft, incorporating the same new design concepts for the wing and empennage boxes but an isogrid design concept fuselage shell, was analyzed in parallel to the same detail. All of the analysis data for this second aircraft is contained in this section with a summary presented in Volume I. The new concept aircraft was considered unresized and again as resized to take maximum advantage of the new concepts. The resized aircraft costs were calculated using a scaled engine based on the off-the-shelf baseline JT8D-17 engine. The baseline aircraft incorporated new metallic materials, but not new design concepts and is described as the "improved baseline" in Volume I.

The acquisition cost generated is the total of development and production phase costs including all of the necessary supporting elements. The life cycle cost includes projected operations and support costs. Total production quantities of 100, 300, and 500 aircraft were considered. Production rates postulated for the three quantity programs were 3, 6, and 9 aircraft per month, respectively.

The information available on the baseline aircraft and generated for the new concept aircraft during the study made possible a much more detailed analysis than is usually possible in a program of this type. Not only were precise structural materials and concepts defined but also the manufacturing processes for fabrication and assembly. For the isogrid design concept, maximum advantage was made of the production background for isogrid spacecraft structures. The overall analytical process illustrated in Figure 27 was followed during this program. The key information documents were the engineering drawings for each structural component (see Section III) and the bid work sheets upon which the manufacturing, quality assurance, tooling, and planning estimates were accumulated.

7.1 ACQUISITION COSTS

The acquisition costs are made up of the following resource elements within the two program phases:

Development	Production
Air Vehicle	Air Vehicle
Project Management	Project Management
Product Support	Product Support
Test Spares	Initial Spares
Packaging, Marking, Shipping	Packaging, Marking, Shipping
ECPS	ECP
Training/Trainers	Training/Trainers
AGE	AGE

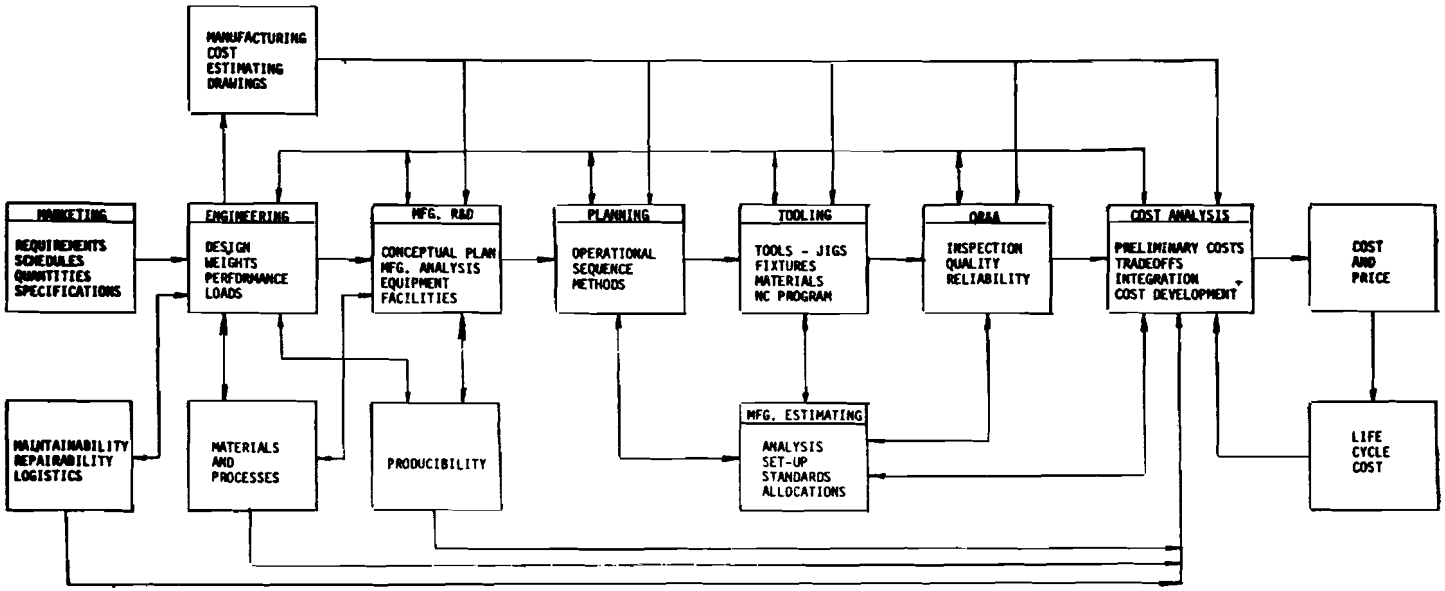


Figure 27 COST ANALYSIS INFORMATION FLOW

Each of these elements was addressed separately during the study. The air vehicle production costs were estimated by a detailed industrial engineering approach made to analyze the fabrication and assembly of major parts. All costs reflect the analyses of the detailed shop standards, the detailed definition of materials and gages, the historical relationships between standard and anticipated actual hours, and the 1973 cost base used which held direct labor, overhead and G&A rates constant.

7.1.1 Labor Hours

As explained in Volume I, bid worksheets were created and the separate planning, tooling, quality assurance, and manufacturing manhour estimates were recorded for each sequenced operation. Figure 28 shows five typical bid worksheets selected from the group that was used to develop the isogrid fuselage fabrication and assembly estimates. Examples for the assembly are contained in the first three bid worksheets (isogrid barrel subassembly Station 590.232 - 710.776, isogrid lower panel subassembly Station 710.776 - 982, and splice to frame wing area). Examples for fabrication are shown in the last two bid worksheets of the figure (segment fuselage shell constant section Station 559 - 703 and segment fuselage shell non-constant section Station 366 - 463). The non-constant sections with double contours impact significantly on the fabrication labor and become most severe in the aft fuselage.

The direct production labor estimates for the baseline and the resized new concept aircraft are shown in Tables XX through XXV. Tables XX, XXI, and XXII are the cumulative average labor hours for the wing, horizontal tail, vertical tail, and fuselage of the baseline aircraft for 100, 300, and 500 aircraft quantities. Tables XXIII, XXIV, and XXV are the same data for resized new concept aircraft with the isogrid fuselage. All estimates for the baseline components are the same as contained in Volume I. Although the design concepts for the wing, horizontal tail, and vertical tail of the new concept aircraft are the same as contained in Volume I, the extimates are slightly higher because of a reduced amount of resizing compared to the aircraft with the honeycomb fuselage. The "remainder" was handled as described In Volume I.

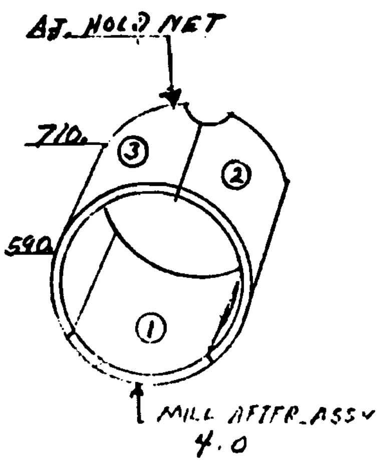
7.1.1.1 Manufacturing - Additional complexity of the application of the isogrid design concept to the fuselage shell from that experienced in spacecraft increased the fabrication cost significantly. These added complexities are the following: (1) variations in skin and rib thicknesses, (2) addition of flanges to the ribs, (3) variations in triangle pattern sizes, and (4) double contours and contour variations. The variations in skin and rib thicknesses and the triangle pattern sizes requires single spindle machining rather than ten-spindle machining as originally conceived at the beginning of the study. The addition of the rib cap flanges in some areas results in an increase of approximately three times the machine time per part. The initial machining pass within a pocket is reduced in size with the flange but can still be accomplished at high cutter speeds. Machining of the volume under the flange, however, involves a change to smaller and less rigid key cutters at a reduced feed rate and an increased number of passes. Forming of the panels to complex contours and relatively small bend radii is a critical factor. In the center section, the radii are within experimentally derived limits and web buckling and cracking do not appear to be a problem. For the aft fuselage, the web heights and smaller radii requirements are beyond presently defined limits.

BID WORK SHEET

MAT'L:		PART NO:	STA 590.232 - 710.776 (FUSE)
SIZE:	TOTAL NO. REQ.	PART NAME:	ISOGRID BARREL SUBASSEMBLY
SPEC:		NEXT ASSEM:	
		END ITEM:	
		CHG. LET.	

PLAN	
Q.C.	
MAT'L.	
PROC.	
TOOL EST.	
MFG. EST.	

PART ILLUSTRATION:



NO.	OPERATION	TOOL	EQUIPMENT	DEPT.	UNIT COST SET-UP	UNIT COST FAB.	UNIT COST ASSEM.	TOOL COST DES.	TOOL COST FAB.
1	LOC PANEL #1						2.0		
2	LOC PANEL #2						2.0		
3	LOC PANEL #3						2.0		
*150	AWB-22-4 BOLT								
150	WCL-22 WASHER								
150	WPL-22 WASHER								
150	LH7461T-048 NUT						14.6		
	*APPROX. REQUIRED BOLTS								
	NOTE: DESIGN A.J. HOLD (3) PIECE SEGMENT. HOLDING NET TO CIRCUMFERENCE AT STA 710.776 A.J. TO MILL SEGMENT AT STA 590.232 AFTER ASSEMBLY.								
	NOTE: BOLT HLS TO BE DRILLED F/S (MUST HAVE TOLERANCE NOT NET FIT) USE DRIFT PUNCH TO ALIGN BOLT HLS FOR INST.								

UNIT COST SUMMARY

SET-UP	HRS
FAB.	HRS
ASSEM.	HRS
MAT'L.	$
CYCLE	DAYS

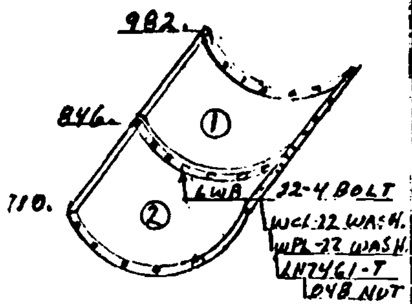
Figure 28 TYPICAL BID WORK SHEET FOR ISOGRID FUSELAGE COST ANALYSIS

BID WORK SHEET

MAT'L:	TOTAL NO. REQ.	PART NO: STA 710.776 - 982 (FUSE)	CHG. LET.
SIZE:		PART NAME: ISOGRID LOWER PANEL ASSEMBLY SUB	
SPEC:		NEXT ASSEM:	
		END ITEM:	

PLAN	
Q.C.	
MAT'L.	
PROC.	
TOOL EST.	
MFG. EST.	

PART ILLUSTRATION:



NO.	OPERATION	TOOL	EQUIPMENT	DEPT.	UNIT COST SET-UP	UNIT COST FAB.	UNIT COST ASSEM.	TOOL COST DES.	TOOL COST FAB.
1	LOC FWD PANEL	H.F.	HOIST				2.0		
2	LOC AFT PANEL	H.F.	HOIST				2.0		
*84	LWB-22-4 BOLT	HAND							
84	WCL-22 WASHER	HAND							
84	WPL-22 WASHER	HAND							
84	LH7461-T-048 NUT	HAND					8.2		
	NOTE: BOLT HOLES TO BE DRILLED FULL SIZE (TOLERANCE REQUIRED) USE DRIFT PUNCH FOR ALIGHMENT OF HL'S & BOLT.								
	NOTE: TOOL DESIGN. H.F. TOOL TO HOLD BOTH PANELS IN A FIXED POSITION DURING ASSEMBLY OPERATION.								
	*APPROX. BOLTS REQUIRED								

UNIT COST SUMMARY

SET-UP		HRS
FAB.		HRS
ASSEM.		HRS
MAT'L.	$	
CYCLE		DAYS

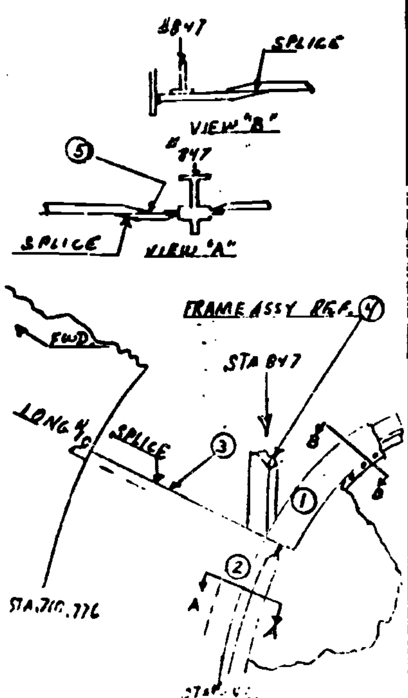
Figure 28 TYPICAL BID WORK SHEET FOR ISOGRID FUSELAGE COST ANALYSIS -- Continued

BID WORK SHEET

MAT'L:	TOTAL NO. REQ.	PART NO:	CHG. LET.
SIZE:		PART NAME: SPLICE TO FRAME WING AREA	
SPEC:		NEXT ASSEM:	
		END ITEM:	

PLAN	
Q.C.	
MAT'L.	
PROC.	
TOOL EST.	
MFG. EST.	

PART ILLUSTRATION:



UNIT COST SUMMARY		
SET-UP		HRS
FAB.		HRS
ASSEM.		HRS
MAT'L.	$	
CYCLE		DAYS

NO.	OPERATION	TOOL	EQUIPMENT	DEPT.	UNIT COST SET-UP	UNIT COST FAB.	UNIT COST ASSEM.	TOOL COST DES.	TOOL COST FAB.
1	SPLICE LH FTG	A.J.					3.00		
1	SPLICE RH FTG	A.J.					3.00		
2	SPLICE LH FTG	A.J.					5.00		
2	SPLICE RH FTG	A.J.					5.00		
3	SPLICE LONG #10 LH	A.J.					6.00		
	SPLICE LONG #10 RH	A.J.					6.00		
4	FRAME LH	A.J.					7.70		
	FRAME RH	A.J.					7.70		
5	SPLICE VIEW A & B		FTG'S TO BE BONDED OVER 100% OF FAYING SURFACE &						
			FASTENED AT NODES WITH 3/16 STL HUCK BOLTS						
			WING/FUSE INTERSECTION A FRONT SPAR SIMILAR						
			TO REAR SPAR						
	A.J. DESIGN TO HOLD BOLT ATTACH +005 AT SPLICE & PANEL ATTACH POINTS								
	(NOTE: ENG. DESIGN CHANGE MAY BE REQUIRED TO DRILL ABOVE ATTACH POINTS								
	FROM A.J.)								

Figure 28 TYPICAL BID WORK SHEET FOR ISOGRID FUSELAGE COST ANALYSIS -- Continued

65-470 (7-64)

PAGE NO: 1 OF 2

BID WORK SHEET

MAT'L: PLATE 7475	TOTAL NO. REQ. 1	PART NO: F.W. 030174	CHG. LET.	PLAN.
SIZE: 1 1/4 X 146 X 240		PART NAME: SEGMENT FUSELAGE SHELL CONSTANT		Q.C.
SPEC:		NEXT ASSEM: SECTION STATION 559-703		MAT'L.
		END ITEM: BARRELS 3, 4, & 5		PROC.
				TOOL EST.
				MFG. EST.

PART ILLUSTRATION:

NOTE: THERE ARE 9 SIMILAR SEGMENTS MILL FIXTURE 1 COMMON MACHINE CONTROL MEDIA 1-1, 2, 3, 4 FOR EACH DRAWING NUMBER

HANDLING FIXTURE COMMON

ATP 2 COMMON AND IS ACTUALLY A COMPLEX MACHINE

NO.	OPERATION	TOOL	EQUIPMENT	DEPT.	UNIT COST SET-UP	UNIT COST FAB.	UNIT COST ASSEM.	TOOL COST DES.	TOOL COST FAB.
1	FURNISH								
2	MILL (1) SIDE	HFPR	SKIN MILL		2.0	3.130			
	TO FLRT	HFLD	12" FLY						
3	MILL OPPOSITE SIDE	HFPR	SKIN MILL		.5	3.130			
	HOLD 1.000 DIM.	HFLD	12" FLY						
4	PROFILE ALL POCKETS	MF1	NC		4.0	46.512			
	NOTE: 3 CONFIGURATIONS	MCM1	SKIN MILL						
	OF ISOGRID ON THIS	MCM2							
	SEGMENT	MCM3							
		MCM4							
	SEC. CC VIEW D	MC1							
	CHANGE CUTTER	MC2							
	CUT FLOOR ATTACH	MC3							
	SURFACE VIEW D								
5	CHANGE CUTTER								
	MACHINE RETURN								
	LIP POCKETS VIEW D.								
	NOTE: 3 CONFIGURATION								
	CHANGE CUTTERS. MACHINE								
	HOLES AT ISOGRID NODES.								

UNIT COST SUMMARY		
SET-UP	10.7/96.3	HRS
FAB.	68.517/616.653	HRS
ASSEM.		HRS
MAT'L.	$	
CYCLE		DAYS

65-470 (7-64)

PAGE NO: 2 OF 2

BID WORK SHEET

MAT'L:	TOTAL NO. REQ.	PART NO: F.W. 030174	CHG. LET.	PLAN.
SIZE:		PART NAME: SEGMENT FUSELAGE SHELL CONSTANT		Q.C.
SPEC:		NEXT ASSEM: SECTION STATION 559-703		MAT'L.
		END ITEM: BARRELS 3, 4, & 5		PROC.
				TOOL EST.
				MFG. EST.

PART ILLUSTRATION:

NO.	OPERATION	TOOL	EQUIPMENT	DEPT.	UNIT COST SET-UP	UNIT COST FAB.	UNIT COST ASSEM.	TOOL COST DES.	TOOL COST FAB.
6	ROUGH TRIM OUTSIDE.								
	ALLOW 1/16 FOR FINISH								
	AFTER FORM								
	(BLANK NO HOLES)								
7	INSPECT								
8	PROTECT								
9	BRAKE FORM	CKF			1.5	5.040			
		ATP1							
	CHECK & STRAIGHTEN				.2	2.000			
10	INSPECT								
11	MACHINE ENDS AND EDGES	ATP2			1.9	1.700			
12	DRILL CIRCUMFERENCE AND	ATP2			.6	7.005			
	AND LONGITUDINAL ATTACH								
	HOLES								
13	INSPECT								
14	PROCESS								

UNIT COST SUMMARY		
SET-UP	SEE SHEET 1	HRS
FAB.		HRS
ASSEM.		HRS
MAT'L.	$	
CYCLE		DAYS

Figure 28 TYPICAL BID WORK SHEET FOR ISOGRID FUSELAGE COST ANALYSIS -- CONTINUED

65-470 (7-64) PAGE NO: 1 OF 2

BID WORK SHEET

MAT'L: PLATE AL 7475	TOTAL NO. REQ.	PART NO: F.W. 03174	CHG. LET.
SIZE: 1 1/4 X 100 X 246		PART NAME: SEGMENT FUSELAGE SHELL NON-CONSTANT	
SPEC:		NEXT ASSEM: SECTION STATION 366 TO 463	
		END ITEM: BARREL ONE	

PLAN.	Q.C.	MAT'L.	PROC.	TOOL EST.	MFG. EST.

PART ILLUSTRATION:

NO.	OPERATION	TOOL	EQUIPMENT	DEPT.	UNIT COST SET-UP	UNIT COST FAB.	UNIT COST ASSEM.	TOOL COST DES.	TOOL COST FAB.
	NOTE: ALL ISOGRID								
	SEGMENTS IN THE FORWARD								
	AND AFT NON-CONSTANT								
	SECTIONS MUST BE MACHINED								
	TO AN EXPANDED FLAT								
	PATTERN THUS PROVIDING								
	CORRECT LOCATION OF								
	ATTACH NODES AFTER SHOT								
	PEEN FORMING.								
1	MILL (1) SIDE TO CLEAN UP	NT	SKIN MILL		2.0	3.0			
		HFPR							
		HFLD							
2	MILL OPPOSITE SIDE	NT			0.5	3.0			
	HOLD 1.000 DIM.								
3	PROFILE ALL POCKETS	MCM1			4.0	37.85			
	NOTE: 3 CONFIGURATION	MCM2							
	ISOGRID THIS PANEL.	MCM3							
		MCM4							
	CHANGE CUTTER MACHINE	MC1							
	FLOOR. ATTACH SUB FLOOR	MC2							
	VIEW D.	MC3							

UNIT COST SUMMARY		
SET-UP	11.4/159.6	HRS
FAB.	71.255/997.570	HRS
ASSEM.		HRS
MAT'L.	$	
CYCLE		DAYS

65-470 (7-64) PAGE NO: 2 OF 2

BID WORK SHEET

MAT'L:	TOTAL NO. REQ.	PART NO: F.W. 03174	CHG. LET.
SIZE:		PART NAME: SEGMENT FUSELAGE SHELL NON-CONSTANT	
SPEC:		NEXT ASSEM:	
		END ITEM:	

PLAN.	Q.C.	MAT'L.	PROC.	TOOL EST.	MFG. EST.

PART ILLUSTRATION:

NOTE: THERE ARE 14 SEGMENTS IN FORWARD AND AFT NON-CONSTANT SECTIONS. EACH DASH NUMBER WILL REQUIRE ITS OWN STRING OF TOOLS.

NO.	OPERATION	TOOL	EQUIPMENT	DEPT.	UNIT COST SET-UP	UNIT COST FAB.	UNIT COST ASSEM.	TOOL COST DES.	TOOL COST FAB.
	CHANGE CUTTERS AND								
	MACHINE. RETURN LIP								
	POCKETS VIEW D. CHANGE								
	CUTTERS AND MACHINE HOLES								
	AT ISOGRID NODES.								
4	DO NOT TRIM.								
5	SHOT PEEN FORM	CKF			2.0	10.00			
		SPNF							
6	ROUGH TRIM	ATP1			1.0	1.700			
7	FINISH TRIM	ATP1			1.0	1.700			
8	DRILL ATTACH HOLES	ATP1			.6	7.005			
9	DEBURR				.3	7.000			
10	INSPECT								
11	PROCESS								

UNIT COST SUMMARY		
SET-UP	SEE SHEET 1	HRS
FAB.		HRS
ASSEM.		HRS
MAT'L.	$	
CYCLE		DAYS

Figure 28 TYPICAL BID WORK SHEET FOR ISOGRID FUSELAGE COST ANALYSIS -- Concluded

TABLE XX DIRECT PRODUCTION LABOR ELEMENT ESTIMATES BASELINE - 100 AIRCRAFT PROGRAM

AIRCRAFT COMPONENT	DIRECT LABOR HOURS PER AIRCRAFT[1]			
	MANUFACTURING	QUALITY ASSURANCE	TOOLING	PLANNING
WING				
Box Structure	55,050	4,517	2,860	3,853
Remainder (Includes also Flaps, Ailerons, Balance Weights)	71,968	6,235	7,970	5,038
Subtotal	127,018	10,752	10,830	8,891
HORIZONTAL TAIL				
Box Structure	9,136	760	731	640
Remainder	9,641	842	1,291	675
Subtotal	18,777	1,602	2,022	1,315
VERTICAL TAIL				
Box Structure	7,031	589	618	492
Remainder	11,751	1,033	1,660	823
Subtotal	18,782	1,622	2,278	1,315
FUSELAGE				
Fuselage Shell and Floor Panels	42,923	3,706	3,990	3,005
Remainder	67,556	5,833	6,279	4,729
Subtotal	110,479	9,539	10,269	7,734
REMAINDER OF AIRCRAFT[2]	98,435	14,340	9,061	6,889
TOTAL	373,491	37,855	34,460	26,144

[1]Cumulative average recurring estimated actual hours

[2]Includes the following airframe systems:

- landing gear (less rolling assembly)
- flight controls
- propulsion (less engine)
- fuel system
- auxiliary power unit
- instruments
- hydraulics
- pneumatics
- electrical
- avionics
- furnishings
- air conditioning
- ice protection
- handling gear

TABLE XXI DIRECT PRODUCTION LABOR ELEMENT ESTIMATES BASELINE - 300 AIRCRAFT PROGRAM

AIRCRAFT COMPONENT	DIRECT LABOR HOURS PER AIRCRAFT[1]			
	MANUFACTURING	QUALITY ASSURANCE	TOOLING	PLANNING
WING				
Box Structure	39,499	3,210	1,651	2,765
Remainder (Includes also Flaps, Ailerons, Balance Weights)	51,638	4,379	4,601	3,615
Subtotal	91,137	7,589	6,252	6,380
HORIZONTAL TAIL				
Box Structure	6,594	540	422	462
Remainder	6,958	593	745	487
Subtotal	13,552	1,133	1,167	949
VERTICAL TAIL				
Box Structure	5,075	418	357	355
Remainder	8,482	727	958	594
Subtotal	13,557	1,145	1,315	949
FUSELAGE				
Fuselage Shell and Floor Panels	30,264	2,573	2,303	2,119
Remainder	47,632	4,050	3,625	3,333
Subtotal	77,896	6,623	5,928	5,452
REMINDER OF AIRCRAFT[2]	68,517	9,838	5,231	4,796
TOTAL	264,659	26,328	19,893	18,526

[1]Cumulative average recurring estimated actual hours

[2]Includes the following airframe systems:

- landing gear (less rolling assembly)
- flight controls
- propulsion (less engine)
- fuel system
- auxiliary power unit
- instruments
- hydraulics
- pneumatics
- electrical
- avionics
- furnishings
- air conditioning
- ice protection
- handling gear

TABLE XXII DIRECT PRODUCTION LABOR ELEMENT ESTIMATES BASELINE - 500 AIRCRAFT PROGRAM

AIRCRAFT COMPONENT	DIRECT LABOR HOURS PER AIRCRAFT[1]			
	MANUFACTURING	QUALITY ASSURANCE	TOOLING	PLANNING
WING				
Box Structure	33,889	2,745	1,305	2,372
Remainder (Includes also Flaps, Ailerons, Balance Weights)	44,303	3,739	3,637	3,101
Subtotal	78,192	6,484	4,942	5,473
HORIZONTAL TAIL				
Box Structure	5,673	463	334	397
Remainder	5,987	506	589	419
Subtotal	11,660	969	923	816
VERTICAL TAIL				
Box Structure	4,366	358	282	306
Remainder	7,297	620	757	511
Subtotal	11,663	978	1,039	817
FUSELAGE				
Fuselage Shell and Floor Panels	25,753	2,178	1,820	1,803
Remainder	40,533	3,429	2,865	2,838
Subtotal	66,286	5,607	4,685	4,641
REMAINDER OF AIRCRAFT[2]	57,951	8,282	4,134	4,056
TOTAL	225,752	22,320	15,723	15,803

[1]Cumulative average recurring estimated actual hours

[2]Includes the following airframe systems:

- landing gear (less rolling assembly)
- flight controls
- propulsion (less engine)
- fuel system
- auxiliary power unit
- instruments
- hydraulics
- pneumatics
- electrical
- avionics
- furnishings
- air conditioning
- ice protection
- handling gear

TABLE XXIII DIRECT PRODUCTION LABOR ELEMENT ESTIMATES RESIZED NEW CONCEPTS, ISOGRID FUSELAGE - 100 AIRCRAFT PROGRAM

AIRCRAFT COMPONENT	DIRECT LABOR HOURS PER AIRCRAFT[1]			
	MANUFACTURING	QUALITY ASSURANCE	TOOLING	PLANNING
WING				
Box Structure	36,535	3,793	2,311	1,830
Remainder (Includes also Flaps, Ailerons, Balance Weights)	70,918	6,219	7,804	4,964
Subtotal	107,453	10,112	10,115	6,797
HORIZONTAL TAIL				
Box Structure	4,625	520	721	234
Remainder	9,549	825	1,230	664
Subtotal	14,174	1,345	1,951	898
VERTICAL TAIL				
Box Structure	4,122	448	539	206
Remainder	11,629	1,022	1,644	814
Subtotal	15,751	1,470	2,183	1,020
FUSELAGE				
Fuselage Shell and Floor Panels	64,225	9,148	5,929	3,365
Remainder	67,181	5,800	6,244	4,703
Subtotal	131,406	14,948	12,173	8,068
REMAINDER OF AIRCRAFT[2]	97,844	14,256	9,027	6,849
TOTAL	366,629	42,131	35,449	24,759

[1]Cumulative average recurring estimated actual hours

[2]Includes the following airframe systems:

- landing gear (less rolling assembly)
- flight controls
- propulsion (less engine)
- fuel system
- auxiliary power unit
- instruments
- hydraulics
- pneumatics
- electrical
- avionics
- furnishings
- air conditioning
- ice protection
- handling gear

TABLE XXIV DIRECT PRODUCTION LABOR ELEMENT ESTIMATES RESIZED NEW CONCEPTS, ISOGRID FUSELAGE - 300 AIRCRAFT PROGRAM

AIRCRAFT COMPONENT	DIRECT LABOR HOURS PER AIRCRAFT[1]			
	MANUFACTURING	QUALITY ASSURANCE	TOOLING	PLANNING
WING				
Box Structure	25,072	2,579	1,334	1,256
Remainder (Includes also Flaps, Ailerons, Balance Weights)	50,887	4,375	4,505	3,562
Subtotal	75,959	6,954	5,839	4,818
HORIZONTAL TAIL				
Box Structure	3,402	367	416	170
Remainder	6,891	585	710	482
Subtotal	10,293	952	1,126	652
VERTICAL TAIL				
Box Structure	3,066	325	311	153
Remainder	8,399	720	949	588
Subtotal	11,465	1,045	1,260	741
FUSELAGE				
Fuselage Shell and Floor Panels	45,371	6,297	3,423	2,377
Remainder	47,367	4,027	3,604	3,316
Subtotal	92,738	10,324	7,027	5,693
REMAINDER OF AIRCRAFT[2]	68,103	9,780	5,211	4,767
TOTAL	258,559	29,055	20,463	16,671

[1]Cumulative average recurring estimated actual hours

[2]Includes the following airframe systems:

- landing gear (less rolling assembly)
- flight controls
- propulsion (less engine)
- fuel system
- auxiliary power unit
- instruments
- hydraulics
- pneumatics
- electrical
- avionics
- furnishings
- air conditioning
- ice protection
- handling gear

TABLE XXV DIRECT PRODUCTION LABOR ELEMENT ESTIMATES RESIZED NEW CONCEPTS, ISOGRID FUSELAGE - 500 AIRCRAFT PROGRAM

AIRCRAFT COMPONENT	DIRECT LABOR HOURS PER AIRCRAFT[1]			
	MANUFACTURING	QUALITY ASSURANCE	TOOLING	PLANNING
WING				
Box Structure	21,058	2,159	1,054	1,055
Remainder (Includes also Flaps, Ailerons, Balance Weights)	43,665	3,730	3,561	3,056
Subtotal	64,723	5,889	4,615	4,111
HORIZONTAL TAIL				
Box Structure	2,950	326	329	153
Remainder	5,928	492	561	408
Subtotal	8,878	818	890	561
VERTICAL TAIL				
Box Structure	2,678	281	246	134
Remainder	7,223	614	750	506
Subtotal	9,901	895	996	640
FUSELAGE				
Fuselage Shell and Floor Panels	38,643	5,401	2,704	2,024
Remainder	40,308	3,410	2,849	2,822
Subtotal	78,951	8,811	5,553	4,846
REMAINDER OF AIRCRAFT[2]	57,598	8,233	4,119	4,132
TOTAL	220,051	24,646	16,173	14,290

[1]Cumulative average recurring estimated actual hours

[2]Includes the following airframe systems:

- landing gear (less rolling assembly)
- flight controls
- propulsion (less engine)
- fuel system
- auxiliary power unit
- instruments
- hydraulics
- pneumatics
- electrical
- avionics
- furnishings
- air conditioning
- ice protection
- handling gear

The most promising forming methods are shot peen and/or age forming. For this study, shot peen forming was selected for estimating but contingencies were included for uncertainties. The estimates also include installation of a suitable pocket filling material to support the ribs. Fabrication includes an allowance of 0.050 inches on some surfaces for chemical milling prior to forming to prevent "oil-canning" of pockets.

7.1.1.2 Planning - Estimates of the direct planning hours were developed after completion of the advanced planning bid worksheets and the recurring and non-recurring direct tooling hour estimates. Direct planning hours include fabrication, assembly, fabrication release, fabrication liaison, assembly release, assembly liaison, and all other. Due to lack of visibility at initial stages, all tool requirements are not fully defined and some adjustments are usually needed to advanced planning estimates. An evaluation of historical data determined the applicable quantitative elements and the required judgmental adjustments for the isogrid fuselage.

The impact of the reduced number of parts primarily affects fabrication planning but, in turn, affects other planning functions. The liaison planning effort, however, is less a function of number of parts as geographical plant locations. Since facility requirements and planning were not included in this study, any beneficial effects are not included. Overall reduction of parts was reflected in the fabrication planning estimates through a reduction of 30 percent. Further reductions could result from additional definition of facilities layouts and numerical control software requirements.

7.1.1.3 Tooling - Non-recurring and recurring tooling hours were estimated based on historical data without influence of the C-15 design-to-cost activity. This was done to provide a direct comparison with contemporary structural design concepts. The tooling estimates for the isogrid fuselage shell considered the manufacturing methods and tool requirements in the detailed advanced planning bid worksheets. Although there was the reduction in numbers of tools required, the remaining tools in most instances are larger and more complex. The isogrid panels (as well as the integrally stiffened panels of the wing and empennage boxes) require larger size holding, hoisting, and transporting racks and fixtures, more complex cutting tools, and vacuum chucks as part of the holding fixture. All tools of this type would be specifically designed for and dedicated to this program. The complexity of numerically controlled programming was anticipated to increase.

7.1.1.4 Quality Assurance - The Quality Assurance (QA) estimates were based on the assumption that existing military specifications will be applicable. Therefore, the labor estimates are consistent with existing requirements for receiving inspection and process control for the baseline and the unchanged portion of the new concept aircraft.

The QA labor was estimated to almost double for the isogrid fabrication compared to the baseline. This is because of the need to include a large amount of NDI with routine fabrication inspection and dimensional checking. Penetrant inspection will be required on all parts. Also, prime plate stock is required involving additional inspection. Tooling inspection increased commensurate with the tool complexity.

7.1.1.5 Other Labor - Engineering, flight test, and product support hours were estimated by the procedures described in Volume I involving consideration of the effects of the design concept and historical experience.

7.1.2 Material Costs

The procedures for calculating the material costs of the isogrid fuselage are described in Volume I. Material unit costs and utilization factors used are shown in Table XXVI. The low utilization factor for 7475 prime plate reflects the large amount of material machined away in isogrid. The resulting effective material cost is $12.25 per pound of finished panel (unit cost divided by the utilization factor). After cleaning and shipping, chip recovery would return about 5 cents per pound and reduce the cost per finished pound to $12.05. This off-set has not been included in the total material cost calculations shown in Tables XXVII through XXXIV. Raw material and purchased part costs per aircraft for the 100, 300 and 500 aircraft programs are summarized in Tables XXXV and XXXVI for the baseline and resized new concept aircraft, respectively. For the 300 aircraft structural components, the cost of material increased from $5.61 per pound for the baseline to $7.92 per pound for the new concept aircraft. For the fuselage only, this cost increased from $3.65 per pound to $7.70 per pound. Tooling, product support and other material costs were estimated as described in Volume I with adjustments for the isogrid concept.

7.1.3 Subcontracts and RDT&E

The baseline engine costs for the JT8D-17 were scaled down by the thrust ratio for the resized new concept aircraft. Avionics costs are the same as in Volume I.

The air vehicle costs for the 100, 300, and 500 aircraft programs were apportioned to research, development, test and evaluation (RDT&E) on the basis of five aircraft being produced utilizing RDT&E funds for each program. Table XXXVII summarizes these costs. These estimates are constant for each of the three aircraft except for peak production rate variation effects on non-recurring tooling and non-recurring planning. A profit of 8 percent has been applied to all the material and labor elements of cost for both the development and production phases. Because engines and avionics are usually considered as GFE, no profit is applied to them.

7.1.4 Air Vehicle Production Costs

The air vehicle production cost estimates for the baseline, unresized new concept, and resized new concept aircraft are shown in Table XXXVIII. The total procurement subtotal is for the program aircraft quantities noted minus the RDT&E costs for the five aircraft included in Table XXXVII. The unit prices shown are the flyaway cumulative average prices for each production quantity.

7.1.5 Other Acquisition Costs

Other elements of acquisition costs were estimated as described in Volume I. Table XXXIX summarizes the total acquisition costs for the baseline and new concept aircraft with the isogrid fuselage for the three quantities of aircraft.

TABLE XXVI MATERIAL UNIT COST		
Material Type	$/Lb	Utilization Factor
Fiberglass & Glass	2.78	0.59
Adhesive	25.66	0.83
Aluminum - 7075 Forging	2.46	0.25
Aluminum - 2024, 7075 Sheet, Plate, Extrusion	1.64	0.81
Aluminum - Honeycomb	8.17	0.83
Aluminum - 7475 Sheet & Prime Plate	2.45	0.20
Aluminum - 7050 Sheet & Plate (Mostly Sheet)	1.78	0.81
Aluminum - 7050 Extrusion	2.05	0.81
Aluminum - 7050 Forging	3.07	0.25
Aluminum - 7049 Forging	2.64	0.25
Aluminum - 7475 Sheet & Plate	1.81	0.81
Steel	1.43	0.35
Titanium	9.19	0.37
Boron - Aluminum (With 7050 Extrusion)	7.72	0.67
Boron	88.88	0.71
Other (Filler, Attachments, Paint, Balance Weight)	4.87	1.00

TABLE XXVII WING COMPONENT RAW MATERIAL COST ESTIMATE, BASELINE - 300 AIRCRAFT PROGRAM

MATERIAL CATEGORY	MATERIAL WEIGHT - LB		COST[1] JANUARY 1973 DOLLARS
	DESIGN	PURCHASED	
Fiberglass & Glass	786	1,336	3,714
Adhesive	-	-	-
Aluminum - 7075 Forging	3,197	12,788	31,458
Aluminum - 2024, 7075 Sheet, Plate, Extrusion	1,811	2,228	3,654
Aluminum - 7050 Sheet & Plate (Mostly Sheet)	3,111	3,827	6,812
Aluminum - 7475 Sheet & Plate	1,987	2,444	4,424
Aluminum - 7049 Forging	1,731	6,924	18,279
Aluminum - 7050 Forging	1,746	6,984	21,441
Aluminum - 7050 Extrusion	-	-	-
Boron - Aluminum (With 7050 Extrusion)	-	-	-
Aluminum - Honeycomb	-	-	-
Steel	681	974	2,747
Titanium	2,930	7,911	72,702
Boron	-	-	-
Other (Filler, Attachments, Paint, Balance Weight)	785	785	3,823
Total	18,765	46,201	169,054

[1] Cumulative Average Estimate

TABLE XXVIII HORIZONTAL TAIL COMPONENT RAW MATERIAL COST ESTIMATE, BASELINE - 300 AIRCRAFT PROGRAM

MATERIAL CATEGORY	MATERIAL WEIGHT - LB		COST[1] JANUARY 1973 DOLLARS
	DESIGN	PURCHASED	
Fiberglass & Glass	-	-	-
Adhesive	-	-	-
Aluminum - 7075 Forging	307	1,228	3,021
Aluminum - 2024, 7075 Sheet, Plate, Extrusion	1,134	1,395	2,288
Aluminum - 7050 Sheet & Plate (Mostly Sheet)	1,073	1,320	2,350
Aluminum - 7475 Sheet & Plate	-	-	-
Aluminum - 7049 Forging	55	220	581
Aluminum - 7050 Forging	-	-	-
Aluminum - 7050 Extrusion	536	659	1,351
Boron - Aluminum (With 7050 Extrusion)	-	-	-
Aluminum - Honeycomb	-	-	-
Steel	-	-	-
Titanium	-	-	-
Boron	-	-	-
Other (Filler, Attachments, Paint, Balance Weight)	129	129	628
Total	3,234	4,951	10,219

[1] Cumulative Average Estimate

TABLE XXIX VERTICAL TAIL COMPONENT RAW MATERIAL COST ESTIMATE, BASELINE - 300 AIRCRAFT PROGRAM

MATERIAL CATEGORY	MATERIAL WEIGHT - LB		COST[1] JANUARY 1973 DOLLARS
	DESIGN	PURCHASED	
Fiberglass & Glass	-	-	-
Adhesive	-	-	-
Aluminum - 7075 Forging	384	1,536	3,779
Aluminum - 2024, 7075 Sheet, Plate, Extrusion	1,455	1,790	2,936
Aluminum - 7050 Sheet & Plate (Mostly Sheet)	890	1,094	1,947
Aluminum - 7475 Sheet & Plate	-	-	-
Aluminum - 7049 Forging	61	244	644
Aluminum - 7050 Forging	-	-	-
Aluminum - 7050 Extrusion	445	547	1,121
Boron - Aluminum (With 7050 Extrusion)	-	-	-
Aluminum - Honeycomb	-	-	-
Steel	94	134	378
Titanium	-	-	-
Boron	-	-	-
Other (Filler, Attachments, Paint, Balance Weight)	131	131	638
Total	3,460	5,476	11,443

[1] Cumulative Average Estimate

TABLE XXX FUSELAGE COMPONENT RAW MATERIAL COST ESTIMATE, BASELINE - 300 AIRCRAFT PROGRAM

MATERIAL CATEGORY	MATERIAL WEIGHT - LB		COST[1] JANUARY 1973 DOLLARS
	DESIGN	PURCHASED	
Fiberglass & Glass	1,315	2,236	6,216
Adhesive	-	-	-
Aluminum - 7075 Forging	-	-	-
Aluminum - 2024, 7075 Sheet, Plate, Extrusion	12,679	15,595	25,576
Aluminum - 7050 Sheet & Plate (Mostly Sheet)	-	-	-
Aluminum - 7475 Sheet & Plate	644	792	1,434
Aluminum - 7049 Forging	2,862	11,448	30,223
Aluminum - 7050 Forging	-	-	-
Aluminum - 7050 Extrusion	5,280	6,494	13,313
Boron - Aluminum (With 7050 Extrusion)	-	-	-
Aluminum - Honeycomb	-	-	-
Steel	527	754	2,126
Titanium	240	648	5,955
Boron	-	-	-
Other (Filler, Attachments, Paint, Balance Weight)	820	820	3,994
Total	24,367	38,787	88,837

[1] Cumulative Average Estimate

TABLE XXXI WING COMPONENT RAW MATERIAL COST ESTIMATE, RESIZED NEW CONCEPT - 300 AIRCRAFT PROGRAM

MATERIAL CATEGORY	MATERIAL WEIGHT - LB		COST[1] JANUARY 1973 DOLLARS
	DESIGN	PURCHASED	
Fiberglass & Glass	774	1,316	3,658
Adhesive	-	-	-
Aluminum - 7075 Forging	3,147	12,588	30,967
Aluminum - 2024, 7075 Sheet, Plate, Extrusion	1,783	2,193	3,597
Aluminum - 7050 Sheet & Plate	2,886	3,550	6,319
Aluminum - 7475 Sheet & Plate	1,842	2,266	4,101
Aluminum - 7049 Forging	1,452	5,808	15,333
Aluminum - 7050 Forging	1,620	6,480	19,893
Aluminum - 7050 Extrusion	-	-	-
Boron - Aluminum (With 7050 Extrusion)	-	-	-
Aluminum - Honeycomb	-	-	-
Steel	670	958	2,702
Titanium	2,884	7,787	71,560
Boron	-	-	-
Other (Filler, Attachments, Paint, Balance Weight)	415	415	2,021
Total	17,473	43,361	160,151

[1] Cumulative Average Estimate

TABLE XXXII HORIZONTAL TAIL COMPONENT RAW MATERIAL COST ESTIMATE, RESIZED NEW CONCEPT - 300 AIRCRAFT PROGRAM

MATERIAL CATEGORY	MATERIAL WEIGHT - LB		COST[1] JANUARY 1973 DOLLARS
	DESIGN	PURCHASED	
Fiberglass & Glass	-	-	-
Adhesive	110	132	3,387
Aluminum - 7075 Forging	304	1,216	2,991
Aluminum - 2024, 7075 Sheet, Plate, Extrusion	1,123	1,381	2,265
Aluminum - 7050 Sheet & Plate	929	1,142	2,034
Aluminum - 7475 Sheet & Plate	-	-	-
Aluminum - 7049 Forging	-	-	-
Aluminum - 7050 Forging	-	-	-
Aluminum - 7050 Extrusion	266	327	671
Boron - Aluminum (With 7050 Extrusion)	-	-	-
Aluminum - Honeycomb	114	137	1,119
Steel	-	-	-
Titanium	-	-	-
Boron	-	-	-
Other (Filler, Attachments, Paint, Balance Weight)	157	157	764
Total	3,003	4,492	13,231

[1] Cumulative Average Estimate

TABLE XXXIII VERTICAL TAIL COMPONENT RAW MATERIAL COST ESTIMATE, RESIZED NEW CONCEPT-300 AIRCRAFT PROGRAM

MATERIAL CATEGORY	MATERIAL WEIGHT - LB		COST[1] JANUARY 1973 DOLLARS
	DESIGN	PURCHASED	
Fiberglass & Glass	--	-	--
Adhesive	59	71	1,822
Aluminum - 7075 Forging	380	1,520	3,739
Aluminum - 2024, 7075 Sheet, Plate, Extrusion	1,441	1,772	2,906
Aluminum - 7050 Sheet & Plate	800	984	1,751
Aluminum - 7475 Sheet & Plate	--	--	--
Aluminum - 7049 Forging	--	--	--
Aluminum - 7050 Forging	--	--	--
Aluminum - 7050 Extrusion	228	280	575
Boron - Aluminum (With 7050 Extrusion)	--	--	--
Aluminum - Honeycomb	133	160	1,307
Steel	-93	133	375
Titanium	--	--	--
Boron	55	77	6,844
Other (Filler, Attachments, Paint, Balance Weight)	67	67	326
Total	3,256	5,064	19,645

[1] Cumulative Average Estimate

TABLE XXXIV ISOGRID FUSELAGE COMPONENT RAW MATERIAL COST ESTIMATE, RESIZED NEW CONCEPT - 300 AIRCRAFT PROGRAM

MATERIAL CATEGORY	MATERIAL WEIGHT - LB		COST[1] JANUARY 1973 DOLLARS
	DESIGN	PURCHASED	
Fiberglass & Glass	1,315	2,236	6,275
Adhesive	--	--	--
Aluminum - 7075 Forging	--	--	--
Aluminum - 2024, 7075 Sheet, Plate, Extrusion	9,545	11,740	19,254
Aluminum - 7475 Sheet & Prime Plate	7,868	39,340	108,972
Aluminum - 7475 Sheet & Plate	--	--	--
Aluminum - 7049 Forging	2,787	11,148	29,431
Aluminum - 7050 Forging	--	--	--
Aluminum - 7050 Extrusion	102	125	256
Boron - Aluminum (With 7050 Extrusion)	1,702	2,553	19,709
Aluminum - Honeycomb	--	--	--
Steel	527	754	2,125
Titanium	--	--	--
Boron	--	--	--
Other (Filler, Attachments, Paint, Balance Weight)	763	763	3,716
Total	24,609	68,659	189,679

[1] Cumulative Average Estimate

TABLE XXXV RAW MATERIALS AND PURCHASED PARTS SUMMARY BASELINE

AIRCRAFT COMPONENT	DESIGN COST WEIGHT LB	JANUARY 1973 DOLLARS[1]		
		100 ACFT PROGRAM	300 ACFT PROGRAM	500 ACFT PROGRAM
WING				
Box Structure	9,118	63,342	53,600	49,596
Remainder (Includes also Flaps, Ailerons, Balance Weights)	9,647	136,437	115,454	106,828
Subtotal	18,765	199,779	169,054	156,524
HORIZONTAL TAIL				
Box Structure	1,749	5,549	4,696	4,345
Remainder	1,485	6,527	5,523	5,110
Subtotal	3,234	12,076	10,219	9,455
VERTICAL TAIL				
Box Structure	1,475	4,836	4,097	3,791
Remainder	1,985	8,681	7,346	6,797
Subtotal	3,460	13,517	11,443	10,588
FUSELAGE				
Center Fuselage Shell, Floor Panels (Sta. 366-982)	7,002	23,371	19,777	18,299
Aft Fuselage Shell (Sta. 982-1437)	2,464	9,838	8,325	7,703
Remainder	14,901	71,773	60,735	56,198
Subtotal	24,367	104,982	88,837	82,200
REMAINDER OF AIRCRAFT[2]	32,229	588,817	498,260	461,035
TOTAL	82,055	919,171	777,813	719,802

[1]Cumulative average estimate

[2]Includes the following airframe systems:

- landing gear (less rolling assembly)
- flight controls
- propulsion (less engine)
- fuel system
- auxiliary power unit
- instruments
- hydraulics
- pneumatics
- electrical
- avionics
- furnishings
- air conditioning
- ice protection
- handling gear

TABLE XXXVI RAW MATERIALS AND PURCHASED PARTS SUMMARY RESIZED NEW CONCEPT - ISOGRID FUSELAGE

AIRCRAFT COMPONENT	DESIGN COST WEIGHT LB	JANUARY 1973 DOLLARS[1]		
		100 ACFT PROGRAM	300 ACFT PROGRAM	500 ACFT PROGRAM
WING				
Box Structure	7,977	54,961	46,508	43,033
Remainder (Includes also Flaps, Ailerons, Balance Weights)	9,496	134,297	113,643	105,153
Subtotal	17,473	189,258	160,151	148,186
HORIZONTAL TAIL				
Box Structure	1,532	9,172	7,761	7,181
Remainder	1,471	6,464	5,470	5,061
Subtotal	3,003	15,636	13,231	12,242
VERTICAL TAIL				
Box Structure	1,290	14,621	12,372	11,448
Remainder	1,966	8,595	7,273	6,730
Subtotal	3,256	23,216	19,645	18,178
FUSELAGE				
Center Fuselage Shell, Floor Panels (Sta. 366-982)	7,100	109,986	93,071	86,118
Aft Fuselage Shell (Sta. 982-1437)	2,692	43,360	36,691	33,950
Remainder	14,817	70,803	59,914	55,437
Subtotal	24,609	224,149	189,676	175,505
REMAINDER OF AIRCRAFT[2]	31,995	584,542	494,643	457,688
TOTAL	80,336	1,036,801	877,346	811,799

[1]Cumulative average estimate

[2]Includes the following airframe systems:

- landing gear (less rolling assembly)
- flight controls
- propulsion (less engine)
- fuel system
- auxiliary power unit
- instruments
- hydraulics
- pneumatics
- electrical
- avionics
- furnishings
- air conditioning
- ice protection
- handling gear

TABLE XXXVII AIR VEHICLE RDT&E COST ESTIMATE COMPARISON (NEW CONCEPTS - ISOGRID FUSELAGE)

RESOURCE ELEMENT	100 AIRCRAFT PROGRAM			300 AIRCRAFT PROGRAM			500 AIRCRAFT PROGRAM		
	BASELINE	UNRESIZED NEW CONCEPT	RESIZED NEW CONCEPT	BASELINE	UNRESIZED NEW CONCEPT	RESIZED NEW CONCEPT	BASELINE	UNRESIZED NEW CONCEPT	RESIZED NEW CONCEPT
LABOR									
MANUFACTURING	83.0	83.3	82.5	83.0	83.3	82.5	83.0	83.3	82.5
TOOLING	51.0	53.5	53.0	75.5	79.0	78.3	93.5	97.6	97.0
PLANNING	10.2	9.9	9.3	16.3	15.9	15.3	21.8	21.2	20.4
QUALITY ASSURANCE	9.4	10.9	10.9	19.5	22.0	21.9	27.2	30.9	30.7
ENGINEERING DESIGN	153.9	138.6	138.5	153.9	138.6	138.5	153.9	138.6	138.5
ENGINEERING LABORATORY	45.0	47.9	47.9	45.0	47.9	47.9	45.0	47.9	47.9
FLIGHT TEST	33.8	36.0	36.0	33.8	36.0	36.0	33.8	36.0	36.0
PRODUCT SUPPORT	14.5	13.3	12.9	14.5	13.3	12.9	14.5	13.3	12.9
SUBTOTAL[2]	400.8	393.4	391.0	441.5	436.0	433.3	472.7	469.0	465.9
MATERIAL									
MANUFACTURING - RAW MATERIALS AND PURCHASED PARTS	17.5	19.7	19.7	17.5	19.7	19.7	17.5	19.7	19.7
EQUIPMENT - INSTRUMENTS AND SPECIAL EQUIPMENT	16.8	16.8	16.7	16.8	16.8	16.7	16.8	16.8	16.7
TOOLING	4.2	4.4	4.4	5.5	5.8	5.8	6.5	6.8	6.8
FLIGHT TEST	5.3	5.6	5.6	5.3	5.6	5.6	5.3	5.6	5.6
PRODUCT SUPPORT	12.3	11.6	11.4	12.3	11.6	11.4	12.3	11.6	11.4
SUBTOTAL[3]	56.1	58.1	57.8	57.4	59.5	59.2	58.4	60.5	60.2
SUBCONTRACTS									
ENGINES	7.5	7.5	7.4	7.5	7.5	7.4	7.5	7.5	7.4
AVIONICS	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
SUBTOTAL	9.7	9.7	9.6	9.7	9.7	9.6	9.7	9.7	9.6
TOTAL PRICE	466.6	461.2	458.4	508.6	505.2	502.1	540.8	539.2	535.7

[1] INCLUDES OVERHEAD, G&A, OVERTIME PREMIUM, DIRECT CHARGES, PROFIT

[2] DIRECT CHARGES, PROFIT

TABLE XXXVIII AIR VEHICLE PRODUCTION COST ESTIMATE COMPARISON (NEW CONCEPTS - ISOGRID FUSELAGE)

RESOURCE ELEMENT	100 AIRCRAFT PROGRAM			300 AIRCRAFT PROGRAM			500 AIRCRAFT PROGRAM		
	BASELINE	NEW CONCEPT UNRESIZED	NEW CONCEPT RESIZED	BASELINE	NEW CONCEPT UNRESIZED	NEW CONCEPT RESIZED	BASELINE	NEW CONCEPT UNRESIZED	NEW CONCEPT RESIZED
LABOR									
MANUFACTURING	549.9	544.0	538.8	1,261.6	1,287.8	1,231.1	1,828.2	1,797.7	1,780.4
TOOLING	131.2	137.5	136.3	194.0	203.2	201.4	240.5	251.0	249.5
PLANNING	79.1	76.8	71.6	126.0	123.1	118.0	168.7	163.8	157.4
QUALITY ASSURANCE	58.0	66.9	66.7	118.9	135.4	134.4	167.0	189.9	188.4
ENGINEERING DESIGN	116.1	104.6	104.5	145.1	130.7	130.6	163.4	147.2	147.1
ENGINEERING LABORATORY	3.1	3.3	3.3	5.1	5.4	5.4	5.5	5.8	5.8
FLIGHT TEST	3.1	3.3	3.3	5.1	5.4	5.4	5.5	5.8	5.8
PRODUCT SUPPORT	4.0	3.8	3.7	5.7	5.4	5.3	6.3	6.0	5.9
SUBTOTAL[1]	944.4	940.2	928.2	1,861.5	1,896.4	1,831.6	2,585.1	2,567.2	2,540.3
MATERIAL									
MANUFACTURING - RAW MATERIALS AND PURCHASED PARTS	84.0	95.5	94.7	239.8	272.6	270.4	379.2	431.1	427.6
EQUIPMENT - INSTRUMENTS AND SPECIAL EQUIPMENT	97.9	97.9	97.2	304.0	304.0	301.8	510.1	510.1	506.4
TOOLING	7.4	7.7	7.7	11.0	11.5	11.4	13.7	14.3	14.2
FLIGHT TEST	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PRODUCT SUPPORT	5.7	5.1	5.0	8.1	7.3	7.2	9.0	8.1	8.0
SUBTOTAL[2]	195.0	206.2	204.6	562.9	595.4	590.8	912.0	963.6	956.2
SUBCONTRACTS									
ENGINES	142.5	142.5	140.5	442.5	442.5	436.2	742.5	742.5	731.9
AVIONICS	42.5	42.5	42.5	131.9	131.9	131.9	221.3	221.3	221.3
SUBTOTAL	185.0	185.0	183.0	574.4	574.4	568.1	963.8	963.8	953.2
TOTAL PROCUREMENT	1,324.5	1,331.4	1,315.8	2,998.8	3,066.2	2,990.5	4,460.9	4,494.6	4,449.7
UNIT PRICE[3]	13,942	14.015	13.851	10.165	10.394	10.137	9.012	9.080	8.989
RDT&E	466.6	461.2	458.4	508.6	505.2	502.1	540.8	539.2	535.7
TOTAL AIR VEHICLE	1,791.1	1,792.6	1,774.2	3,507.4	3,571.4	3,492.6	5,001.7	5,033.8	4,985.4

JANUARY 1973 DOLLARS, MILLIONS

[1] INCLUDES OVERHEAD, G&A, OVERTIME PREMIUM, DIRECT CHARGES, PROFIT

[2] INCLUDES DIRECT CHARGES, PROFIT

[3] FLYAWAY PRICE ONLY

TABLE XXXIX ACQUISITION COST COMPARISON (NEW CONCEPTS - ISOGRID FUSELAGE)

RESOURCE ELEMENT	100 AIRCRAFT PROGRAM			300 AIRCRAFT PROGRAM			500 AIRCRAFT PROGRAM		
	BASELINE	UNRESIZED NEW CONCEPT	RESIZED NEW CONCEPT	BASELINE	UNRESIZED NEW CONCEPT	RESIZED NEW CONCEPT	BASELINE	UNRESIZED NEW CONCEPT	RESIZED NEW CONCEPT
DEVELOPMENT									
AIR VEHICLE	439.8	436.3	434.1	481.8	480.3	477.8	514.0	514.3	511.4
PROJECT MANAGEMENT	28.8	28.6	28.5	31.6	31.5	31.4	33.7	33.8	33.5
PRODUCT SUPPORT	26.8	24.9	24.3	26.8	24.9	24.3	26.8	24.9	24.3
TEST SPARES	28.3	28.1	28.0	30.8	30.8	30.6	32.8	32.8	32.6
PKG. MRKG. SHPG.	.9	.8	.8	.9	.9	.9	1.0	1.0	1.0
ECPS	17.6	17.5	17.4	19.3	19.2	19.1	20.6	20.6	20.5
TRAINING/TRAINERS	16.8	16.9	16.7	27.5	28.1	27.4	39.1	39.4	39.0
AGE	15.8	15.9	15.7	40.3	41.2	40.2	66.6	67.1	66.5
SUBTOTAL	574.8	569.0	565.5	659.0	656.9	651.7	734.6	733.9	728.8
PRODUCTION									
AIR VEHICLE (PME)	1,314.8	1,322.5	1,307.1	2,985.0	3,053.5	2,978.0	4,445.6	4,480.5	4,435.8
PROJECT MANAGEMENT	23.0	23.2	22.9	52.2	53.5	52.1	77.8	78.4	77.6
PRODUCT SUPPORT	9.7	8.9	8.7	13.8	12.7	12.5	15.3	14.1	13.9
INITIAL SPARES	116.2	116.6	115.3	294.8	298.9	293.2	460.9	463.0	458.3
PKG. MRKG. SHPG.	3.5	3.5	3.5	8.9	9.0	8.8	13.8	13.9	13.7
ECP	52.6	552.9	52.3	119.4	122.2	119.1	177.9	179.2	177.4
TRAINING/TRAINERS	25.2	25.4	25.1	41.2	42.1	41.1	58.7	59.2	58.5
AGE	23.7	23.8	23.5	60.5	61.8	60.3	99.9	100.7	99.7
SUBTOTAL	1,568.7	1,576.8	1,558.4	3,575.8	3,653.7	3,565.1	5,349.9	5,389.0	5,335.9
ACQUISITION TOTAL	2,143.5	2,145.8	2,123.8	4,234.8	4,310.6	4,216.8	6,084.5	6,122.9	6,063.9

JANUARY 1973 DOLLARS, MILLIONS

7.2 LIFE CYCLE COSTS

7.2.1 Operating Factors and Maintenance Manpower

The operational costs of the system were projected using the Air Force "Planning Aircraft Cost Estimating" (PACE) model (Reference 7) for forces of 100, 300, and 500 aircraft operating for 20 full force years without any phase-in or phase-out phenomenon. In the 100 aircraft case, 15 aircraft were withheld for pipeline advanced attrition and command and support purposes, 44 aircraft were withheld for the 300 case, and 73 aircraft for the 500 case. The remaining unit equipment (UE) aircraft were organized into squadrons of 16 aircraft each. Since full squadrons could not be held for the 100 and 500 aircraft cases, fractional squadrons were used for these two cases to maintain data comparability. Each UE aircraft operates 900 hours per year.

The most significant single component of operating costs is the personnel required to operate the system. The determination of personnel begins with establishing the anticipated maintenance manhours per flying hour for the aircraft under consideration in the operating environment. Table XL displays the estimated maintenance manhours per flight hour for the baseline aircraft and the unresized and resized new concept configuration. The airframe maintenance function manpower requirements shown vary in response to the changed maintenance requirements as a result of the new concept structure. While these estimates are preliminary, they are based upon detailed considerations of the structural problems and advantages associated with the various new concepts used in the major structural portions of the airplane wing, horizontal stabilizer, vertical stabilizer, and fuselage. As shown in the table, the maintenance manhours for propulsion are a function of the thrust level. Avionics maintenance was, of course, held constant.

The results from the PACE model were used to provide a comparative total maintenance analysis. These results are summarized in Table XLI. The changes in the maintenance manhours per flight hours per flying hour together with the changes in spares costs produce an increase of 35 million for the unresized new concept aircraft and $5.6 million for the resized new concept aircraft over the life of the system. These increases are 1.5 percent and 0.2 percent, respectively, from the baseline aircraft.

7.2.2 Total Life Cycle Costs

The total life cycle costs for the baseline and the unresized and resized new concept aircraft are shown in Table XLII for 100, 300, and 500 aircraft in the total procurement period. The acquisition costs displayed here are from Table XXXIX. The operations and support costs were derived from applying the PACE model utilizing the maintenance manhour per flying hour inputs and the spares support factors. Fuel cost was 15 cents per gallon as reported in AMF173-10 for fiscal year 1973. Although it is anticipated that fuel costs have now advanced to significantly higher levels the 1973 point was used to maintain comparability with the remainder of the cost data.

7.3 NEW CONCEPT ECONOMIC BENEFITS

The implicit labor and material cost complexity factors for the new concept aircraft with the honeycomb fuselage are described in Volume I. The

TABLE XL MAINTENANCE MAN-HOURS PER FLIGHT HOUR COMPARISON NEW CONCEPTS - ISOGRID FUSELAGE)

MAINTENANCE FUNCTIONS	BASELINE AIRCRAFT	NEW CONCEPT UNRESIZED	NEW CONCEPT RESIZED
AIRFRAME	3.13	3.21	3.08
PROPULSION	3.62	3.62	3.58
AVIONICS	1.77	1.77	1.77
SUBTOTAL	8.52	8.60	8.43
SERVICING	2.70	2.70	2.70
CLEANING/ CORROSION CONTROL	0.28	0.28	0.28
SUPPORT OTHER	0.45	0.45	0.45
SUBTOTAL	3.43	3.43	3.43
PRE/POST FLIGHT	0.57	0.57	0.57
PHASE (PH) INSPECTION (LOOK)	0.98	0.98	0.98
SUBTOTAL	1.55	1.55	1.55
TOTAL	13.50	13.58	13.41

TABLE XLI COMPARISON OF MAINTENANCE COSTS FOR 300 AIRCRAFT PROGRAM (NEW CONCEPTS - ISOGRID FUSELAGE)

MAINTENANCE COST ELEMENT	BASELINE AIRCRAFT	NEW CONCEPT UNRESIZED	NEW CONCEPT RESIZED
REPLENISHMENT SPARES	290.3	295.4	288.8
MODIFICATION/SPARES	233.6	239.1	233.2
COMMON AGE/SPARES	31.7	31.7	31.7
SYSTEM SUPPORT MATERIAL	290.3	295.3	288.8
GENERAL SUPPORT MATERIAL	188.9	192.4	187.1
SUBTOTAL	1,034.8	1,053.9	1,029.6
MAINTENANCE PERSONNEL	588.1	565.3	560.3
DEPOT MAINTENANCE	753.9	792.8	792.8
SUBTOTAL	1,342.0	1,358.1	1,353.1
TOTAL	2,376.8	2,412.0	2,382.7
COMPARISON WITH BASELINE	1.000	1.015	1.002

JANUARY 1973 DOLLARS, MILLIONS
256 OPERATING AIRCRAFT

TABLE XLII LIFE CYCLE COST COMPARISON (NEW CONCEPTS - ISOGRID FUSELAGE)

RESOURCE ELEMENTS	BASELINE	NEW CONCEPT	
		UNRESIZED	RESIZED
100 AIRCRAFT QUANTITY			
ACQUISITION	2,143.5	2,145.8	2,123.8
OPERATIONS AND SUPPORT			
DIRECT			
MATERIALS/SPARES	467.5	468.2	463.3
PERSONNEL	434.9	427.3	425.6
POL	520.2	518.7	515.6
DEPOT MAINTENANCE	250.3	263.2	263.2
MISCELLANEOUS	5.0	4.9	4.9
INDIRECT			
BASE OPERATING SUPPORT	214.3	213.5	211.9
PLANNING ADDITIVES	32.7	32.1	31.9
SUBTOTAL	1,924.9	1,927.9	1,916.4
LIFE CYCLE COST	4,068.4	4,073.7	4,040.2
300 AIRCRAFT QUANTITY			
ACQUISITION	4,234.8	4,310.6	4,216.8
OPERATIONS AND SUPPORT			
DIRECT			
MATERIALS/SPARES	1,035.1	1,054.0	1,029.6
PERSONNEL	1,309.8	1,287.0	1,281.9
POL	1,566.7	1,562.1	1,552.9
DEPOT MAINTENANCE	753.9	792.8	792.8
MISCELLANEOUS	15.0	14.7	14.6
INDIRECT			
BASE OPERATING SUPPORT	645.5	643.3	638.3
PLANNING ADDITIVES	98.5	96.6	96.0
SUBTOTAL	5,424.5	5,450.5	5,406.1
LIFE CYCLE COST	9,659.3	9,761.1	9,623.0
500 AIRCRAFT QUANTITY			
ACQUISITION	6,084.5	6,122.9	6,063.9
OPERATIONS AND SUPPORT			
DIRECT			
MATERIALS/SPARES	1,536.6	1,542.3	1,528.8
PERSONNEL	2,184.7	2,146.7	2,138.2
POL	2,613.2	2,605.6	2,590.2
DEPOT MAINTENANCE	1,257.4	1,322.4	1,322.4
MISCELLANEOUS	25.0	24.5	24.4
INDIRECT			
BASE OPERATING SUPPORT	1,076.7	1,073.0	1,064.5
PLANNING ADDITIVES	164.3	161.1	160.2
SUBTOTAL	8,857.9	8,875.6	8,828.7
LIFE CYCLE COST	14,942.4	14,998.5	14,892.6

JANUARY 1973 DOLLARS - MILLIONS

corresponding complexity factors for the new concept resized aircraft with the isogrid fuselage are shown in Tables XLIII and XLIV for the 300 aircraft quantity. The labor factors range from 0.454 for wing box planning to 2.447 for fuselage shell quality assurance. Material cost factors range from 0.868 for the wing box structure to 4.706 for the fuselage shell structure. The wing and empennage factors differ from those presented in Volume I slightly because of the difference in resizing between the honeycomb and isogrid fuselage aircraft. The fuselage factors for the new concepts are significantly higher than the baseline fuselage and the honeycomb fuselage. These higher factors, of course, reflect the impact of the isogrid design concept with its requirements for machining from plate stock and the forming complexities. The two operations counteract the effect of the large reduction in number of parts. These conclusions are specifically for the AMST configuration and are not necessarily the same for other aircraft configurations having a longer constant section and a low wing location. The scaling factors, S_F, necessary to determine the cost coefficients, C_c, as discussed in Volume I, may be determined from the component weights shown in Tables XXXV and XXXVI.

The economic benefits of the new design concepts, in dollars, are listed in Table XLV for each structural component of the resized aircraft. Also shown in the table are the weights and the ratios of the cost changes to the weight changes. All of the components were reduced in weight and cost except the fuselage shell and floor. The new concept fuselage component increased 66.7 percent in cost over the baseline and about $1,378 per pound of weight added. The cost for the wing box was reduced 34.5 percent, for the horizontal stabilizer box, 42 percent, and for the vertical stabilizer box, 29 percent. The respective cost savings per pound of weight saved were approximately $245, $263, and $174. Although the cost of the wing, horizontal stabilizer, and vertical stabilizer boxes was reduced $390,000, or 35 percent, the total for these and the fuselage shell and floor was increased $59,000, or about 3.3 percent. This is because the cost of the new concept fuselage component increased $449,000 (66.7 percent) over the baseline. When the effects of resizing of the remainder of the structure are included, the total cost of structure increased $31,000, or about 7 percent.

TABLE XLIII IMPLICIT LABOR COMPLEXITY FACTORS FOR RESIZED NEW CONCEPT AIRCRAFT RELATIVE TO BASELINE AIRCRAFT (ISOGRID FUSELAGE - 300 AIRCRAFT PROGRAM)

AIRCRAFT COMPONENT	MANUFACTURING	QUALITY ASSURANCE	TOOLING	PLANNING
WING				
Box Structure	0.636	0.803	0.808	0.454
Remainder (Includes also Flaps, Ailerons, Balance Weights)	0.985	0.999	0.979	0.985
Subtotal	0.833	0.916	0.934	0.755
HORIZONTAL TAIL				
Box Structure	0.516	0.680	0.986	0.368
Remainder	0.990	0.987	0.953	0.990
Subtotal	0.759	0.840	0.965	0.687
VERTICAL TAIL				
Box Structure	0.604	0.778	0.871	0.431
Remainder	0.990	0.990	0.991	0.990
Subtotal	0.846	0.913	0.958	0.781
FUSELAGE				
Fuselage Shell & Floor Panels	1.499	2.447	1.486	1.122
Remainder	0.994	0.994	0.994	0.995
Subtotal	1.191	1.559	1.185	1.044
REMAINDER OF AIRCRAFT[1]	0.994	0.994	.996	.994
TOTAL	0.977	1.104	1.029	0.900

[1] Includes the following airframe systems:

- o landing gear (less rolling assembly)
- o flight controls
- o propulsion (less engine)
- o fuel system
- o auxiliary power unit
- o pneumatics
- o electrical
- o avionics
- o furnishings
- o air conditioning
- o instruments
- o hydraulics
- o ice protection
- o handling gear

TABLE XLIV IMPLICIT MATERIAL COST COMPLEXITY FACTORS RESIZED NEW CONCEPT RELATIVE TO BASELINE AIRCRAFT (ISOGRID FUSELAGE - 300 AIRCRAFT PROGRAM)

AIRCRAFT COMPONENT	COMPLEXITY FACTOR
WING	
Box Structure	0.868
Remainder (Includes also Flaps, Ailerons, Balance Weights)	0.984
Subtotal	0.947
HORIZONTAL TAIL	
Box Structure	1.653
Remainder	0.990
Subtotal	1.295
VERTICAL TAIL	
Box Structure	3.020
Remainder	0.990
Subtotal	1.453
FUSELAGE	
Center Fuselage Shell (Stations 366 to 982) and Floor Panels	4.706
Aft Fuselage Shell (Stations 982 to 1437)	4.407
Remainder	.986
Subtotal	2.135

TABLE XLV COST AND WEIGHT BENEFITS OF NEW CONCEPTS (ISOGRID FUSELAGE)

STRUCTURAL COMPONENT	WEIGHT - LB			PRODUCTION COST - $MILLIONS			Δ$/ΔLB
	BASELINE	RESIZED NEW CONCEPT	REDUCTION	BASELINE	RESIZED NEW CONCEPT	COST	
Wing Box	9,118	7,977	1,141	0.865	0.567	-0.298	-245.02
Horizontal Stabilizer Box	1,749	1,532	217	0.143	0.083	-0.060	-263.03
Vertical Stabilizer Box	1,475	1,290	185	0.111	0.079	-0.032	-174.15
Fuselage Shell and Floor	9,466	9,792	-326	0.673	1.122	+0.449	[1377.57]
Component Total	21,808	20,591	1,217	1.792	1.851	+0.059	48.48
Aircraft Structure Total	49,826	48,341	1,485	4.448	4.479	+0.031	20.88

300 AIRCRAFT CUMULATIVE AVERAGE COSTS

[ ] COST ADDED PER POUND ADDED

SECTION VIII

AIRCRAFT PERFORMANCE PAYOFF

The structural arrangement of the aircraft used in the following performance analysis consists of the following new design concepts: (1) integrally stiffened wing cover skins (Concept #1), (2) isogrid fuselage shell and (3) honeycomb sandwich empennage cover skins.

8.1 PERFORMANCE ANALYSIS

The performance payoff studies were conducted for three configurations of aircraft utilizing the new design concepts. These include: (1) unresized, or fixed, geometry; (2) completely resized airframe, including "rubberized" engines; and (3) partially resized airframe with the baseline engines.

8.1.1 Unresized Aircraft

The unresized aircraft has the same external dimensions and engine thrust as the baseline aircraft. The weight reduction of 1080 lb. is due to a combination of new materials and internal geometry changes. This structural weight reduction results in a performance improvement over the baseline aircraft. The improvement may be taken as a reduction in field length, an increase in payload, or as an increase in mission radius. These performance improvement options are summarized in Table XLVI.

8.1.2 Resized Aircraft

The resized aircraft is the minimum weight configuration that has the same performance characteristics as the baseline aircraft. The reduction in structural weight has a cascading effect on total weight as the aircraft is resized. The wing and empennage areas are reduced, and the engines are smaller. Engine weight and performance are those of the JT8D-17 scaled linearly to the required size. The external geometry of the fuselage does not change due to the requirements of cargo space.

The total operator's weight empty reduction obtained by completely resizing the aircraft is 1970 lbs. The description of the resized aircraft is given in Table XLVII.

The reduced wing area cuts the ferry range some 19 nautical miles due to less fuel volume available in the resized wing.

8.1.3 Resized Aircraft with Fixed Engine Thrust

The fixed engine thrust configuration was sized to minimize weight by reducing wing and empennage areas. This allows a greater wing, horizontal tail and vertical tail area reduction relative to the completely resized aircraft.

The total operator's weight empty saved by using the baseline engine is 1850 lbs. The ferry range is reduced some 50 nautical miles (31 less than the completely resized aircraft) due to the smaller wing. The description of the partially resized aircraft is found in Table XLVII.

TABLE XLVI UNRESIZED AIRCRAFT PERFORMANCE IMPROVEMENT OPTIONS				
OPTION	MID-POINT GROSS WEIGHT (LBS)	PAYLOAD CAPABILITY (LBS)	RADIUS CAPABILITY (N.MI.)	FIELD LENGTH MID-POINT (SL 103°F)
BASELINE	150,000	27,000	400	2,000
1	150,000	**28,080**	400	2,000
2	150,000	27,000	**433**	2,000
3	**148,830**	27,000	400	**1,975**

TABLE XLVII RESIZED AIRCRAFT PERFORMANCE DATA			
AIRCRAFT DESCRIPTION	BASELINE AIRCRAFT	COMPLETELY RESIZED AIRCRAFT	PARTIALLY RESIZED (FIXED ENGINE SIZE)
Payload (lb)	27,000	27,000	27,000
Radius (N.Mi.)	400	400	400
Field Length, SL (103°F)(Ft)	2,000	2,000	2,000
Wing Area (Ft^2)	1,740	1,697	1,671
Horizontal Tail Area (Ft^2)	643	632	626
Vertical Tail Area (Ft^2)	462	454	457
Thrust/Eng., SL (103°)(Lb)	14,900	14,532	14,900
Operators Empty Weight (Lb)	103,240	99,850	100,090
Mid-Point Weight (Lb)	150,000	146,310	146,570
Ferry Range (N.Mi.)	2,420	2,390	2,337

SECTION IX

CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations are based on the study experience and the data presented in Sections II through VIII.

9.1 STRUCTURAL DESIGN

9.1.1 Conclusions

- Two structural advantages of isogrid are: (1) it acts in an isotropic manner; and, (2) all of the members resist the loads allowing development of unframed structure. Hence, there is a minimum of parasitic structure.

- The AMST has: (1) a high wing; (2) a fuselage-mounted landing gear; and, (3) a relatively short fuselage with a large portion of non-constant sections which also have out-of-round areas. These factors penalize isogrid such that an isogrid fuselage is not competitive weightwise for the AMST.

- Isogrid wing panels are not competitive weightwise with conventional panel construction since the loads are predominately spanwise which is the orientation of the conventional stringers. (See "pseudo-isogrid" recommendation.)

- Cutout reinforcements in isogrid are easily provided by an integral beefup of the skins and ribs around the cutouts without addition of parts.

- The node holes provide a convenient and weight-effective means of attaching floors, frames, subassemblies, and equipment (i.e., a "peg board" for attachment).

- Isogrid panels should be as large as possible to reduce the joint penalties.

9.1.2 Recommendations

- Isogrid structural applications should be investigated which are flat or singly curved and have sufficiently high load or rigidity requirements to eliminate minimum gage skins. Weight and cost benefits will result if these criteria are met.

- The applicability of "pseudo-isogrid" should be studied. These patterns involve angles other than 60 degrees and variable rib depth thus more effectively orientating the rib material in the primary load direction. Wing panels subjected to high shear loads in combination with high axial loads are a potential candidate.

- A sandwich of two isogrid sheets separated by trusses or webs should be studied for potential weight savings. Candidate applications are: (1) the AMST fuselage in the region of the tail (to replace the tail frames); and (2) under the wing.

- Detailed isogrid studies are required: (1) to determine the potential weight saving using rib orientations determined by different combinations of axial, hoop, and pressure loads; and, (2) to develop the use of the nodes as a "pegboard pattern" for the attachment of provisions thus eliminating bracketry.

- A study of high-low ribbed isogrid in lightly loaded regions should be made, using a rigorous analytical method just completed, to further evaluate the weight saving potential associated with shallow ribs within a high rib pocket.

- A study is required to replace the skin/stringer fuselage loads with isotropic fuselage loads to obtain more realistic stress distributions in the region of the isogrid fuselage/wing intersection to reduce weight (a FORMAT analysis which was beyond the scope of this study).

9.2 STRUCTURAL ANALYSIS

9.2.1 Conclusions

- Isogrid is relatively simple to analyze because it acts as a monocoque sheet with a modified thickness and modulus of elasticity. This property allows use of existing monocoque buckling equations (with the modified thickness and modulus).

- Isogrid possesses advantages in fatigue and damage tolerance associated with all integral structure in that the number of holes (a potential source of initial flaws) is considerably reduced from that of conventional built-up structure. Where applicable, required attachments to the isogrid panels are made in the reinforcement lands which are machined integral with the sheet.

9.2.2 Recommendations

- Some additional analysis methods are required to facilitate the design of isogrid structures. Table XLVIII presents a matrix of available and/or required analytical solutions and tests of isogrid structures. As indicated, the existing information is largely oriented toward the effective design of cylindrical space boosters. These data are suitable for sizing a fuselage to the general overall loads but incomplete where the fuselage is loaded significantly by out-of-plane loads. These are denoted in the Table as "Cylinder-Concentrated Load" and "Cylinder-Distributed Load". Analytical tools (other than finite element analyses) and test verification are required to describe stress states in monocoque cylinders with variable wall thickness when subjected to point or distributed loadings.

TABLE XLVIII MATRIX OF AVAILABLE ANALYTICAL SOLUTIONS AND TEST DATA FOR ISOGRID STRUCTURE

STRUCTURE/MODE ITEM	THEORY		OPTIMIZATION		TEST VALIDATION	
	Unflanged	Flanged	Unflanged	Flanged	Lexan	Metal
Cylinders in Compression	yes	yes	yes	no	yes	yes
Cylinders in Compression and Torsion	yes	yes	no	no	yes	no
Cylinders in Bending	yes	yes	yes	no	yes	yes
Cylinders in Bending and Torsion	yes	yes	no	no	yes	no
Cylinders in Torsion	yes	yes	yes	no	yes	no
Cylinders - Uniform External Pressure	yes	yes	yes	no	yes	no
Spherical Caps - External Pressure	yes	yes	yes	no	yes	yes
In-Plane Concentrated Load - Center of Sheet	yes	yes	yes	no	no	yes
In-Plane Concentrated Load - Edge of Sheet	yes	yes	yes	no	no	no
Cutout Reinforcement	yes	yes	yes	no	yes+	yes+
Open Isogrid Shear Web	yes	yes	yes	no	no	no
Open Isogrid Cylinders - Compr. & Bend.	yes	yes	yes	no	no	no
Open Isogrid Plates - Bending	yes	yes	yes	no	no	yes*
Skinned Isogrid Plates - Bending	yes	yes	yes	no	yes*	no
Skinned Isogrid Plates - Transverse Shear	no	no	no	no	no	no
Elliptical Caps - Uniform External Pressure	no	no	no	no	no	no
Edge Fixity Coefficients - Skin Pockets	no	no	no	no	yes	no
Cylinder - Concentrated Load	yes	yes	no	no	yes•	yes•
Cylinder - Distributed Load	no	no	no	no	no	no
Frustum of Cone - Concent. or Distr. Load	no	no	no	no	no	no
Finite Element Analysis	Has been analysed using Nastran.					
Fatigue Tests	Limited fatigue test data.					
Damage Tolerance	Analyzed using linear elastic fracture mechanics techniques					

(NOTE: + Delta; * Extensional Stiffness only; • Tangential Load only.)

In addition, the unavailable analysis and test items in Table XLVIII covering open and skinned isogrid shear webs should be investigated for shear flow intensities up to at lease 3000 #/in. (the range determined in the present study). Isogrid is basically a three bar linkage which is stable thus providing excellent resistance to shear. In skinned isogrid, the ribs (carrying shear loads), with their centroid spaced away from the skin, in effect form a second surface of a torque box providing greater torsional stiffness than that of conventional construction.

- Tests are required to validate the analysis methods when they are developed. This testing can be done very economically compared to tests of conventional structures. Isogrid's isotropic property allows low cost simulation using Lexan monocoque models. Lexan is a plastic which buckles without permanent set. Hence, one model can be repeatedly tested and reinforced or changed by glueing on additional material for further testing. Stress states can be measured by strain gages. Pertinent Lexan tests would include: (1) buckling to develop interaction equations; (2) stress states away from out-of-plane loads; and, (3) stress states around holes. Isogrid full-scale metal testing is more economical since its integral construction and use of the node holes for equipment attachment eliminates many parts and the failures associated with them. For example, an isogrid compression test basically measures three failure modes; general instability of the overall structure, rib crippling, and skin pocket buckling.

9.3 MANUFACTURING METHODS

9.3.1 Conclusions

- Machining should be by computer-controlled multiple-spindle equipment. This involves a generalized master computer program and a library of isogrid pocket configurations. Using input data on the particular design, the computer selects the applicable pocket dimensions, inputs them into the generalized program, which then commands the spindles to produce the proper part.

- Close tolerance machining is necessary since the isogrid weight is penalized if tolerances are too large.

- The minimum cutter size sets the node hole radii to dimensions larger than required by analysis thus increasing the weight penalty.

- Forming procedures are:

  a. Single curvature: by brake forming or age forming.

  b. Double curvature: by shot peening.

c. Minor double curvature: by bulge forming.

d. Drape forming is size limited.

9.3.2 Recommendations

- Double curvature forming technology requires development, in particular, the shot peen forming of large parts.

9.4 NON-DESTRUCTIVE INSPECTION

9.4.1 Conclusions

- Existing techniques are suitable for inspecting isogrid. These include penetrants to check for cracks, and ultrasonic or eddy-current to check skin and web thicknesses.

9.4.2 Recommendations

- The thickness measuring function should be incorporated with the machining function.

9.5 COST ANALYSIS

9.5.1 Conclusions

- Isogrid costs are increased by mixing different pocket sizes or by capping the ribs

- Isogrid costs are increased by double curvature applications.

9.5.2 Recommendations

- Pocket patterns could be simplified, e.g., replace a tapered pattern by a stepped pattern, to expedite manufacture and reduce cost. (Note: Isogrid space booster costs were less than for conventional construction because there were few parts and repetitive machining was used.)

- Other splice joint design options should be developed which may reduce cost.

9.6 AIRCRAFT PERFORMANCE PAYOFF

9.6.1 Conclusions

- Performance payoff and/or aircraft resizing was indicated in this study using integral stiffened wing covers, an isogrid fuselage, and honeycomb sandwich empennage cover skins. The unresized aircraft had improved performance over the baseline aircraft. The resized aircraft had the same performance characteristics as the baseline, however, a resized aircraft with fixed engine thrust had a shorter ferry range.

APPENDIX A

COMPUTER PROGRAMS

[NATLOC] Normal and Tangential Loads on Cylinders

This program computes in-and-out-of-plane stresses, strains and displacements in a monocoque cylindrical shell when loaded by uniformly distributed radial pressures and shearing loads applied in discrete rectangular pads of loading.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Results of a study program to evaluate application of the isogrid structure concept to a medium STOL transport aircraft are presented. Isogrid is an integrally stiffened panel concept incorporating a triangular arrangement of the stiffening material which has been used successfully on space vehicle structure. The fuselage shell structure of the projected C-15 production airplane is used as the study (and baseline) component. The isogrid concept is evaluated for structural integrity, weight, manufacturing methods, applica-

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) bility of NDI methods, production and life cycle costs, and aircraft performance payoffs. Structural integrity analyses of both the isogrid and the baseline concepts are based on a common set of requirements for ultimate strength, fatigue, and damage tolerance. Because of generally lower stress levels and a general absence of rivet and bolt holes in basic isogrid structure, fatigue and damage tolerance are of reduced criticality relative to baseline structure.

Aluminum materials (7475 plate selected) are the best choice for minimum production cost and weight for isogrid. The isogrid concept, as applied to the C-15 fuselage, however, is shown to be penalized in cost and weight by the following adverse configuration characteristics: (1) high wing and fuselage mounted landing gear which require heavy supporting frames; (2) significant areas of non-circular fuselage section which also require additional frames; (3) significant fuselage areas of double contour shape which result in increased forming costs; and, (4) low panel loadings which result in minimum gage machining constraints. The isogrid fuselage shell is approximately six percent heavier and 65 percent costlier to produce on a participating structure basis. Cost estimates are based on a 'bottom-up' detailed analysis approach for labor and materials. Applications of isogrid to other structural components on an engineering judgment basis are also considered.

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